Technical Document to Support a Water Reservation Rule for the North Fork of the St. Lucie River

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South Florida Water Management District
West Palm Beach, Florida

Executive Summary

The St. Lucie Estuary and the North Fork of the St. Lucie River are located within a watershed that covers approximately 780 square miles located within Martin and St. Lucie counties and a small portion of Okeechobee County along Florida's east coast. Both of these water bodies are tributaries to the southern Indian River Lagoon, which hosts the greatest species diversity of any estuary in North America including 35 species listed as threatened or endangered. These two water bodies have been designated as an Aquatic Preserve and Outstanding Water by the State of Florida and are part of the U.S. Environmental Protection Agency's National Estuary Program.

Over the past 70 years this once highly productive ecosystem has been heavily impacted by drainage and development. High density drainage systems and construction of major drainage canals (C-23, C-24, C-25, and C-44) have drained the land for agriculture and urban development. These drainage projects have greatly increased the volume of runoff discharged to the estuary resulting in wide fluctuations in salinity, degraded water quality, and impacts to estuarine aquatic life.

The Indian River Lagoon – South Project was authorized as part of the Comprehensive Everglades Restoration Plan (CERP) to address the problem of high volume discharges to the estuary. The North Fork of the St. Lucie River represents an important component of the Indian River Lagoon – South Project. A major goal of the project is to reduce damaging freshwater discharges by capturing and attenuating the flows in project reservoirs and stormwater treatment areas and redistributing them to the North Fork of the St. Lucie River in a manner that will help restore the river and its floodplain and also protect oysters and other estuarine biota downstream in the St. Lucie Estuary.

The purpose of this document is to summarize the technical information, methods, and models that were used to develop a water reservation rule for the North Fork of the St. Lucie River. A water reservation rule is a legal mechanism that can be used to set aside water for the protection of fish and wildlife or public health and safety from consumptive use. Under Florida law, the reservation is composed of a quantification of the water to be protected, which includes a seasonal and a geographical component. Once adopted, the reservation rule will be used by the South Florida Water Management District's consumptive use permitting program to evaluate permit applications within the St. Lucie watershed.

As part of the rule development process, an independent expert panel reviewed the information contained in this report and other documents and determined that "…the analysis provided in the draft report provides a sound technical basis for reserving water to protect targeted fish and wildlife…."

The District used a resource-based approach to develop a water reservation for the North Fork of the St. Lucie River. Technical evaluations included a summary of the available literature, review of empirical data, and development of watershed and hydrodynamic models that were used to (a) define hydrologic targets for the river and (b) quantify the volume of available water produced by the project. The District's technical approach consisted of five basic steps:

1) **Identification of key ecological compartments within the St. Lucie Estuary that could benefit from establishment of a water reservation.** Review of available information showed that the North Fork of the St. Lucie River was the most important compartment identified due to its sensitivity to low flows/high salinity conditions and its importance as a nursery area for larval and juvenile fishes (**Section 6**).

2) **Identification of fish and wildlife resources or habitat to be protected.** A combination of the valued ecosystem component approach and the habitat overlap concept was used to focus on critical estuarine habitat needed to protect fish and wildlife within the North Fork of the St. Lucie River. Together, they formed the basis for relating freshwater releases from the upstream watershed to the selected valued ecosystem component (the low salinity zone) and other estuarine resources (**Section 6**). The low salinity zone of an estuary typically occurs where fresh and saline

waters meet with salinities typically ranging from 0 to 10 psu. In this study the low salinity zone was identified as critical habitat for larval and juvenile fishes and was selected as the valued ecosystem component based on the following relationships:

- The low salinity zone represents a highly productive area that is critical to the life histories of many estuarine and marine organisms, serves as important nursery habitat for larval and juvenile fishes, and provides protection from marine predators.
- Contains an estuarine turbidity maximum and a chlorophyll *a* maximum that serves as an abundant food source for both zooplankton and benthic invertebrate organisms, which become prey for larval and juvenile fishes.
- Serves as habitat for a broad array of other estuarine species and represents an important resource in terms of commercial, recreational, and ecosystem value.

3) **Identification of performance measure and flow targets.** A hydrodynamic model (CH3D) was used to simulate a series of pulsed flow releases to the North Fork of the St. Lucie River. This method was chosen to maintain the low salinity zone within the best available habitat identified as an area located between the Kelstadt and Prima Vista bridges. Maintaining a dynamic distribution of the 1 psu isohaline between these two locations was chosen as the salinity performance measure for the North Fork of the St. Lucie River because it relates to the expected location of both the estuarine turbidity maximum and chlorophyll *a* maximum, two ecologically important components of the low salinity zone. Using results from the CH3D model, a time series of pulsed freshwater inflows delivered from the Ten Mile Creek Basin (Gordy Road Structure) that equates to a mean monthly flow of 130 cfs was identified as the flow target for the North Fork of the St. Lucie River (**Section 7**).

4) **Quantification of water made available by the project.** An integrated modeling framework utilizing a combination of the St. Lucie Estuary Watershed (WaSh) and Reservoir Optimization (OPTI-6) models to produce a 41-year daily time series of flow resulting from the Indian River Lagoon – South Project. These models produced two time series known as the 2050 Future with Project and 2050 Future without Project Condition representative of average, wet, and dry hydrologic conditions (**Section 7**).

5) **Quantification of water to be reserved for the protection of fish and wildlife.** The 2050 Future with Project Condition daily time series was converted to mean monthly flows values (to match the target's metric). The resulting data were plotted as volume probability curves and compared to the flow target (mean monthly flow of 130 cfs). Based on these analyses, all dry season flows equal to or less than target flow was reserved for the protection of fish and wildlife (**Sections 8 and 9**). Model results showed that with construction of the Indian River Lagoon – South Project, the mean monthly flow target of 130 cfs is expected to occur more than 90 percent of the time. This will increase the frequency that the 1 psu isohaline will occur within the preferred location between the Kelstadt and Prima Vista bridges. All water in the 2050 Future with Project Condition time series less than the North Fork dry season flow target (130 cfs) was quantified as reserved for the protection of fish and wildlife. Water above the 130 cfs target may be available for allocation to other water users.

The analysis of the information presented in this document identifies water to be reserved for the protection of fish and wildlife in the North Fork of the St. Lucie River. The reservation will be reviewed and revised as necessary in light of changed conditions and as required by law

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Section 1. Introduction

1.1 Purpose and Scope of this Document

This document summarizes the technical and scientific data, assumptions, models, and methods used to support developing a rule to reserve water for the North Fork of the St. Lucie River and its watershed. A water reservation is a legal mechanism that sets aside water from consumptive use to protect a natural resource or the public interest. In this case, the reservation is intended to protect native fish and wildlife. The reservation consists of a quantification of the water to be protected, which includes a seasonal and geographical component.

The South Florida Water Management District (SFWMD or District) intends to use the technical relationships and evaluations identified in this document and the Indian River Lagoon – South Project Implementation Report and Environmental Impact Statement (USACE and SFWMD 2004) as the basis of a water reservation rule for the North Fork of the St. Lucie River. The information contained in this document provides:

1) A brief description of the Indian River Lagoon – South Project features, goals and objectives
2) A description of the water body, its watershed and its biological resources
3) A review of critical biological components that characterize the ecosystem (valued ecosystem components)
4) The development of hydrologic performance measures and targets used to measure how well the plan meets its project objectives
5) A summary of simulated hydrologic conditions within the project area and outflows to the North Fork of the St. Lucie River and downstream estuary for the expected condition in 2050 with all features of the project implementation report completed (termed the 2050 Future with Project Condition) and compared to the hydrologic targets
6) A quantification of the water to be reserved for the protection of fish and wildlife under state law for the North Fork of the St. Lucie River in support of the Comprehensive Everglades Restoration Plan (CERP).

The SFWMD is undertaking the reservation of water for the North Fork of the St. Lucie River as part of its commitments to the Indian River Lagoon – South Project. These commitments were codified for CERP implementation in Section 601(h)(4) of the Water Resource Development Act of 2000 (WRDA 2000) and in Sections 385.26-27 of the Programmatic Regulations for Implementation of the Comprehensive Everglades Restoration Plan (33 Code of Federal Regulations Part 385). The purpose of this process is to ensure that each CERP project provides the intended benefits for the natural system, which requires the identification of water for the natural system including water to be reserved or allocated. This identification includes water available to the natural system prior to project implementation (water that the state has agreed to protect but is not mandated to protect by Section 601(h) of WRDA 2000) and water made available for the natural system as a result of the project (water that is required to be protected by Section 601(h) of WRDA 2000). The SFWMD has elected to use its reservation authority (Section 373.223(4), F.S.) to protect both water available to the natural system prior to project implementation and water made available by the project, and will undertake this protection in a single rulemaking process.

Once adopted, the water reservation will be used by the District's consumptive use permitting program to evaluate permit applications within the St. Lucie River watershed. The reservation rules will require applicants to provide reasonable assurances that their proposed use of water will not withdraw water that is reserved for the protection of fish and wildlife. In essence, the water that is reserved for the protection of fish and wildlife within the North Fork of the St. Lucie River will not be allocated for human use.

The proposed reservation is based on technical information contained within specific related source documents. The information has been used to establish relationships among freshwater flows discharged from the watershed, salinity, and downstream estuarine ecologic response. An independent expert panel reviewed this report and related documents and assessed whether the best currently available technical information supports the relationship between the waters expected to result from the completed CERP project and water needed to be reserved to protect fish and wildlife. The panel's final report and recommendations, public comments, and a summary of the District's responses are provided in **Appendix A** of this document. The reader is encouraged to review the following source documents for additional details:

- Indian River Lagoon – South Project Implementation Report and Environmental Impact Statement (USACE and SFWMD 2004)
  http://www.evergladesplan.org/pm/studies/irl_south_pir.aspx
- St. Lucie River Watershed Protection Plan (SFWMD et al. 2008)
  http://www.sfwmd.gov/pls/portal/docs/PAGE/COMMON/PDF/NE_SLRWPP.PDF
- St. Lucie Estuary and Indian River Lagoon Conceptual Model (Sime 2005)
  http://www.evergladesplan.org/pm/recover/cems.aspx
- Upper East Coast Water Supply Plan, 2006 Amendment (SFWMD 2006)
  http://www.sfwmd.gov/portal/page?_pageid=1874,4166906,1874_4165053:1874_4165220&_dad=portal&_schema=PORTAL
- Indian River Lagoon Surface Water Improvement and Management Plan (Steward et al. 1994)
  http://www.sfwmd.gov/portal/page/portal/pg_grp_sfwmd_watershed/portlet%20-%20coastal%20ecosystems/tab1806037/73ec5d84f811fb33e040e88d49523b6b
- Technical Documentation to Support Development of Minimum Flows for the St. Lucie River and Estuary (SFWMD 2002)
  http://www.sfwmd.gov/portal/page/portal/pg_grp_sfwmd_watersupply/portlet%20-%20st%20lucie%20river%20and%20estuary/tab1608162/stluciemf-maindoc.pdf

1.2 Reservation Water Body and Watershed

The North Fork of the St. Lucie River is the subject of the proposed water reservation (**Figure 1.1**). Water from the North Fork joins water from the South Fork near the U.S. 1–Roosevelt Bridge and moves east to the mid-estuary. Flow then enters the lower St. Lucie Estuary where it intersects with the Indian River Lagoon and is finally discharged to the Atlantic Ocean at the St. Lucie Inlet. The watershed of the St. Lucie Estuary is approximately 780 square miles. The river, estuary, and watershed are described in further detail in **Section 4**.

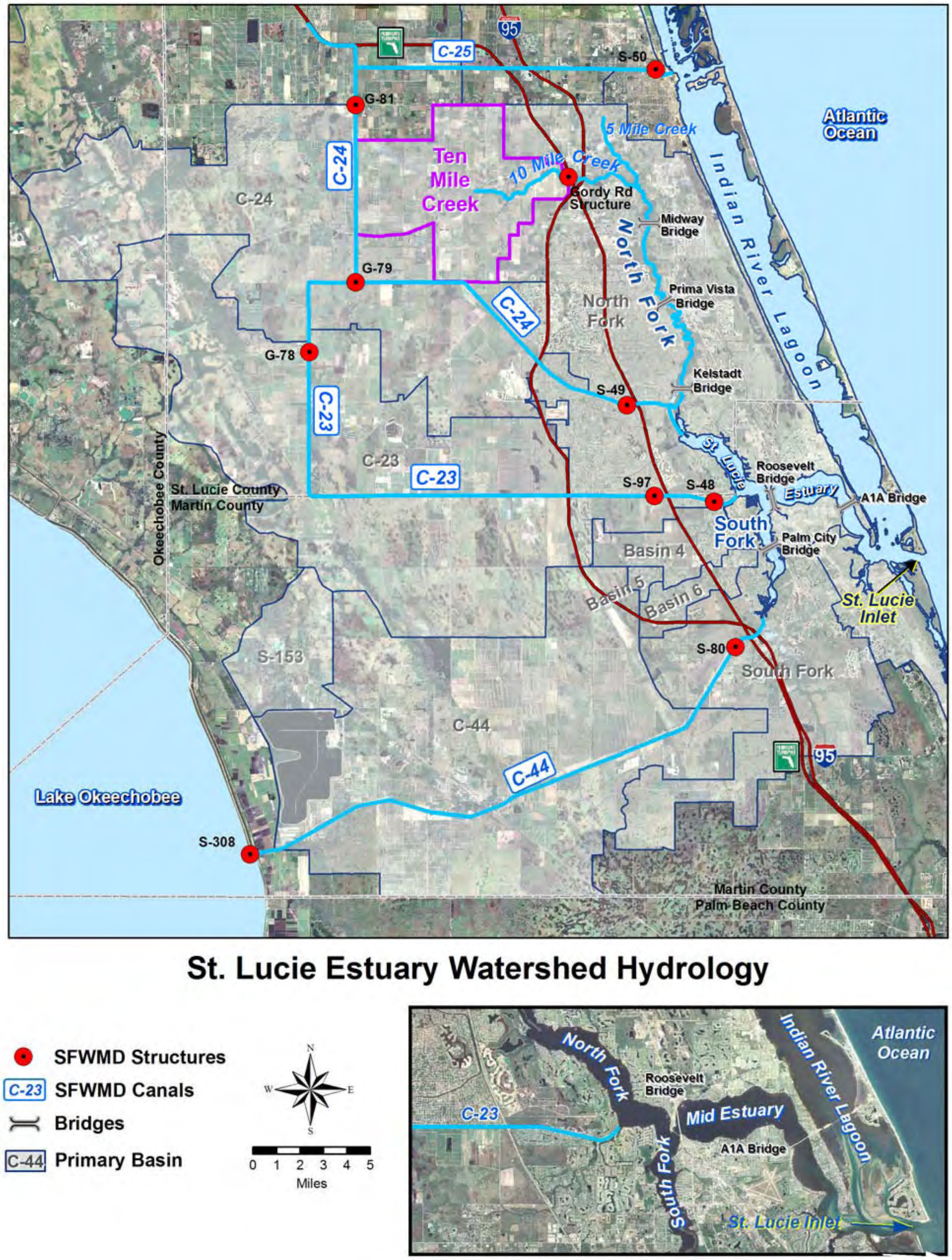

Figure 1.1. St. Lucie Estuary, its tributaries, and its watershed.

1.3 General Technical Approach

A resource-based approach was used to develop the water reservation for the North Fork of the St. Lucie River. The technical evaluation included a summary of available empirical data, modeling analyses, and relevant literature. The approach consisted of the following five basic steps:

1) Identification of the key ecological compartments within the St. Lucie River that could potentially be affected by the reservation
2) Identification of the fish and wildlife resources or habitat to be protected
3) Identification of the salinity performance measure and flow target that will protect fish and wildlife
4) Quantification of the water made available by the project over a timeframe representative of average, wet, and dry hydrologic conditions
5) Quantification of the water to be reserved for the protection of fish and wildlife

The identified reservation water body (Step 1) is described in **Section 4**. The overall technical approach used to develop the water reservation is detailed in **Section 5**. The specific fish and wildlife resources to be protected (Step 2) through the reservation of water are identified in **Section 6**. The development of hydrologic performance measures and targets (Step 3) are presented in **Section 7**. The simulation of future hydrologic conditions within the watershed (Step 4) for Future with and without Project Conditions is also presented in **Section 7**. The results of models used to simulate basin hydrology and compare the performance measures (Step 4) with water made available by the project are provided in **Section 8**, while **Section 9** presents a volume probability curve (Step 5) that quantifies the portion of water needed to be reserved to protect fish and wildlife. The SFWMD has used a similar approach to establish water reservations for Picayune Strand and Fakahatchee Estuary (SFWMD 2009a) and the Kissimmee River and Chain of Lakes (SFWMD 2009b).

An independent expert panel reviewed the information contained in this report and the project implementation report and assessed whether currently available scientific information is adequate for the SFWMD to move forward to develop a water reservation rule for the North Fork of the St. Lucie River. The panel's recommendations, public comments, and a summary of the District's responses are available in **Appendix A** of this report.

1.4 Key Assumptions

The technical approach applied by the SFWMD to quantify water needed for the protection of fish and wildlife within the St. Lucie Estuary was based on the Indian River Lagoon – South Project Implementation Report and Environmental Impact Statement (USACE and SFWMD 2004). A series of assumptions were carried forward from that study and additional ones were identified in this process.

The Indian River Lagoon – South Project was not designed to accommodate regulatory releases from Lake Okeechobee (the Lake Okeechobee watershed covers more than 4,000 square miles). As a result, the Indian River Lagoon – South Project and associated C-44 and C-23/C-24 Reservoirs and stormwater treatment areas were designed to capture, store, and attenuate surface water runoff from the local St. Lucie Watershed. Essentially, the Indian River Lagoon – South Project meets its goals and objectives by retaining water and attenuating flow entering the St. Lucie Estuary resulting in improved salinity and water quality. Appendix J of the project implementation report concluded that certain waters the project delivered for the natural system needed protection by the state. These waters are delivered to (1) the oligohaline (less than 5 practical salinity units) portion of the North Fork during the dry season, (2) maintain the functions of the stormwater treatment areas, and (3) restore ecological functions of the natural storage and treatment areas. The analysis presented within this report focuses solely on identifying water from the C-23/C-24 North and South Reservoirs and Stormwater Treatment Area to restore the North Fork of the St. Lucie River. The project implementation report did not identify water from the C-25 or C-44 Reservoirs to be protected. Water necessary to maintain stormwater treatment areas associated with the C-44 Reservoir is already protected under other regulations, specifically the Lake Okeechobee Water Availability Rule (pursuant to the District's allocation authority under Chapter 373, F.S), which caps allocation of surface water withdrawals from Lake Okeechobee to a base condition water use determined as of January 1, 2008. Water necessary to restore the ecological functions of the natural storage and treatment areas originally identified in the project implementation report will be protected by future rule makings by the District as appropriate.

Analyses of the North Fork of the St. Lucie River (Ten Mile Creek Basin) focus on the Gordy Road Structure. This structure is located nearest to the C-23/C-24 Reservoirs and Stormwater Treatment Area and represents a primary control point for redistributing flows to the downstream estuary. Providing a more natural distribution of flows to the St. Lucie Estuary via the historic North Fork flow-way is an important goal of the Indian River Lagoon – South Project.

The Indian River Lagoon – South Project Implementation Report and Environmental Impact Statement was completed in 2004. Since then, a large body of additional information and model simulations has been developed to support St Lucie Estuary restoration efforts. This document incorporates the most updated available information to date, including information obtained from the St. Lucie Watershed Protection Plan (SFWMD et al. 2008) and additional modeling and analyses developed to specifically support reservation rule development as explained in **Section 7** of this report. This includes developing hydrologic performance measures and a flow target for the North Fork of the St Lucie Estuary.

The revised performance measure for the North Fork focuses on the ecological needs of larval and juvenile fish during South Florida's dry season (November 1 to May 31). Under existing conditions, the St. Lucie Estuary receives too much water during the wet season, which impacts estuarine biota while consumptive use demands are low. As a result, the SFWMD is not recommending establishment of a water reservation for wet season flows delivered to the St. Lucie Estuary.

The existing condition used in this document is assumed to be similar to results of modeling the 2050 Future without Project Condition. This is because agricultural water demands, which are the primary user of surface water in the watershed, are not expected to increase and may actually decrease as predicted in the Upper East Coast Regional Water Supply Plan, 2006 Amendment (see **Section 4 and 7**)(SFWMD 2006).

Section 2.
Basis for Water Reservation

2.1 What Is a Water Reservation?

A water reservation is a legal mechanism to set water aside from consumptive use for the protection of fish and wildlife or public health and safety. The reservation is a quantification of the water to be protected, which includes a seasonal and a location component. For purposes of this report, the SFWMD will be adopting a water reservation for the protection of fish and wildlife for the North Fork of the St. Lucie River by rule. The technical information and recommendations in this document serve as the basis for the quantification of water for the protection of fish and wildlife that will be adopted through the rulemaking process.

The SFWMD has committed to protect the quantities of water necessary for each CERP project to meet its objectives. Section 601(h)(4) of WRDA 2000 requires the state to reserve or allocate the water made available from a CERP project using the authority granted to the State of Florida under Chapter 373 F.S. before a project partnership agreement with the U.S. Army Corps of Engineers (USACE) to construct the project can be executed. In addition, the SFWMD has agreed to use its water reservation or allocation authority to protect existing water for the natural system that is needed for each CERP project. The SFWMD has the ability to use either water reservation or other allocation tools to protect the water previously identified in the Indian River Lagoon – South Project Implementation Report and Environmental Impact Statement (USACE and SFWMD 2004). The SFWMD has determined that a water reservation is the most appropriate tool for protecting water identified for the natural system for this project. For this project, this quantity of water is identified in **Section 9** of this report. A more detailed discussion of the federal authorities applicable to CERP projects can be found in Section 1 and Appendix J of the Indian River Lagoon – South Project Implementation Report and Environmental Impact Statement (USACE and SFWMD 2004).

2.2 Statutory Authority for Establishing Water Reservations

Section 373.223(4), provides the following authority for establishing a water reservation:

> *The governing board or the department, by regulation, may reserve from use by permit applicants, water in such locations and quantities, and for such seasons of the year, as in its judgment may be required for the protection of fish and wildlife or the public health and safety. Such reservations shall be subject to periodic review and revision in the light of changed conditions. However, all presently existing legal uses of water shall be protected so long as such use is not contrary to the public interest.*

When water is reserved under this statute, it is not available to be allocated for use under a consumptive use permit and is protected for the natural system or public health and safety. For purposes of this document, water for protection of fish and wildlife means water for "ensuring a healthy and sustainable, native fish and wildlife community; one that can remain healthy and viable through natural cycles of drought, flood and population variation" (Association of Florida Community Developers, et al. v. Department of Environmental Protection., et al., DOAH Case No. 04-0880RP, Division of Administrative Hearings Final Order Feb. 24, 2006, affirmed 943 So. 2d 989 [Fla 4th DCA 2006]).

The legislature of the State of Florida gave the SFWMD Governing Board broad discretion when establishing a water reservation by specifically authorizing the Governing Board to exercise its judgment.

This discretion is appropriate given the inherent uncertainties associated with linking fish and wildlife and their water needs over a period of time and seasonally. Such discretion allows the Governing Board to address risk and uncertainty within each specific reservation. This interpretation is bolstered by the direction to periodically review and revise the reservation. Such discretion is also helpful in reconciling scientific uncertainties associated with defining the water needs of fish and wildlife.

In quantifying water to be reserved, existing legal uses of water are protected so long as they are not contrary to the public interest. An existing legal use is a water use that is authorized under a consumptive use permit under Part II of Chapter 373, F.S, or is exempt from consumptive use permit requirements.

It is also important to understand what a water reservation does not do. Part II, Chapter 373, F.S. covers authorizations related to the consumptive use of water and includes the authority to establish reservations. The SFWMD's authority to act as local sponsor of a CERP project is found in Part I Chapter 373.1501, F.S. The provisions of Part II do not authorize the District to establish criteria for operations of a CERP project. For CERP projects, Section 385.28 of the Programmatic Regulations for the Implementation of CERP (33 Code of Federal Regulations Part 385) requires that the operating plans for projects be consistent with the state's water reservation or allocation. While the CERP project operational criteria and the water reservation are related, they derive from distinct federal and state authorities.

Water reservations will be adopted by the SFWMD by rule, which it is authorized to do by the Florida Legislature to implement provisions of the Florida statutes. When adopting rules, the SFWMD must not act beyond the powers, functions, and duties delegated to it by the legislature. Further, the District may only adopt rules that implement a specific law.

Courts look to a number of factors set forth in Chapter 120, F.S., to determine whether a proposed District rule is an invalid exercise of delegated legislative authority. These factors, in pertinent part, include whether (1) the agency has exceeded its grant of rulemaking authority, (2) the rule enlarges, modifies or contravenes the specific provisions of law implemented, (3) the rule is vague, fails to establish adequate standards for agency decisions or vests unbridled discretion in the agency, or (4) the rule is arbitrary or capricious. Since the arbitrary and capricious test has been of particular relevance to previous peer review processes, a clear understanding of this standard is appropriate. A rule is arbitrary if it is not supported by logic or the necessary facts; a rule is capricious if it is adopted without thought or reason or is irrational. Rules beyond these parameters would constitute an invalid exercise of delegated legislative authority and would not withstand a rule challenge proceeding.

The SFWMD, as the agency charged with the responsibility of implementing the reservations statute, will be afforded deference in its interpretation of the subject statute. Consequently, the proposed reservations rules should be upheld if they are within the range of permissible interpretations. However, courts will determine a rule to be "arbitrary" if it is not supported by facts or logic or is despotic (Florida League of Cities, Inc. v. Department of Environmental Regulation, 603 So. 2d 1363 [Fla. 1st DCA 1992]). The "capricious" test examines whether a decision is taken irrationally, or without thought or reason (Attorney's Title Insurance Fund v. Financial Services Commission, DO AH Case No. 07-5387 RP [Fla. Div. of Admin. Hrgs., June 25, 2008], see also Board of Clinical Laboratory Personnel v. Florida Association of Blood Banks, 721 So. 2d 317. 318 [Fla. 1st DCA 1998]). For example, in Attorney's Title, the administrative law judge invalidated a proposed rule as arbitrary and capricious, in part, because it relied on a premium rate report that was "...premised in unfounded assumptions and unverifiable data" (Attorney's Title at 79). Similarly, the administrative law judge in Florida Medical Association versus Department of Health, found the proposed rule in that case was arbitrary and capricious because the board:

> *...neither conducted nor reviewed any studies or treatises and received no evidence to support the definition of therapeutic equivalent in the proposed rule, and likewise reviewed no studies as to the safety or benefits / detriments of having a pharmacist substitute a drug for one prescribed by the physician. DOAH Case No. 06-2899RP (Fla. Div. of Admin. Hrgs., Nov. 1,2006, p. 33).*

A final example concerns Florida Power and Light's challenge of a proposed Florida Department of Environmental Protection (FDEP) rule regarding multi-state trading of pollutant emissions. In this instance, the administrative law judge upheld the proposed rule. The judge particularly noted the FDEP's numerous public meetings, thoughtful consideration of public comments and complex policy issues, and the careful weighing and balancing of these issues before concluding the FDEP did not act arbitrarily or capriciously when adopting the rule (Florida Power and Light v. Department of Environmental Protection, DOAH Case No 06-2871RP [Fla. Div. of Admin. Hrgs., March 1, 2007, p. 61], affirmed 970 So. 2d 401 [Fla. 3rd DCA 2007]).

Therefore, it is the SFWMD's responsibility to conduct studies and analysis to identify linkages of water to fish and wildlife protection. There can be multiple answers, methods, and interpretations, but ultimately those selected must be within the realm of acceptable solutions within the statutory authority granted to conduct rule development. During the peer review process, the panel was not asked to attempt to identify a single or best scientific solution, nor address matters of policy, which rest with the Governing Board of the District. Rather, the panel focused its evaluation on all scientific or technical data, methodologies, and models, including all scientific and technical assumptions employed in each model, used to establish a reservation to determine if this reservation proposal is reasonable.

2.3 Process Steps and Activities

This document has been created to support the Florida Statutes Chapter 120 and Sections 373.044 and 373.113 rule development authorities. **Figure 2.1** summarizes the general steps of the rule development process. The SFWMD Governing Board authorized publication of a notice of rule development of a reservation for water for the natural system identified for the Indian River Lagoon – South Project in February 2008 and amended it in April 2008.

This document fulfills the second and third step. The SFWMD has made the determination to have this document, which contains the technical underpinnings used to identify the water needed for the protection of fish and wildlife, peer reviewed by an independent scientific panel as part of the rule development process. As a result of this public process, the final peer review report was used to revise and refine this document.

A public rule development process for stakeholders and interested persons will be conducted to present findings of the peer review and provide the public with opportunities to participate in the drafting of rule language, including specific language quantifying the volume, timing, and distribution of water needed for the protection of fish and wildlife and provisions restricting consumptive use permit allocations. Once the draft rule language has been finalized, the SFWMD Governing Board will have the opportunity to authorize the notice of rulemaking and subsequently hold a public hearing adopting the final rule.

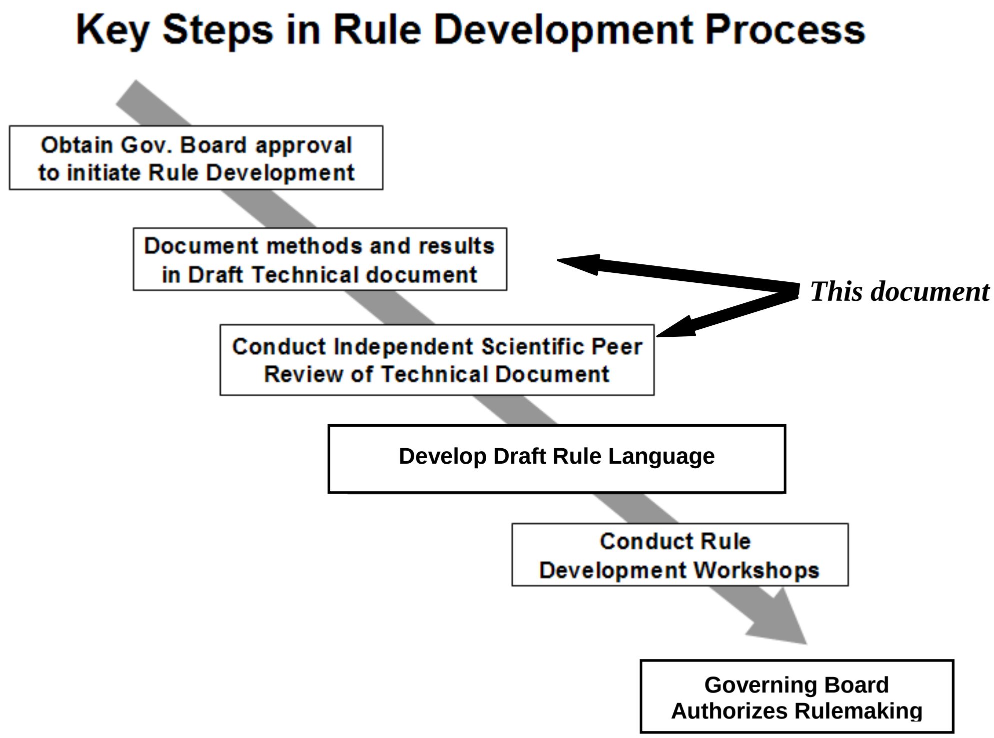

Figure 2.1. Process steps for developing technical information in support of a rule.

Section 3.
Indian River Lagoon – South
Project Area and Scope

3.1 Project Area

The Indian River Lagoon – South Project area includes the portion of the Indian River Lagoon that extends from the St. Lucie-Indian River county line to the Martin-Palm Beach county line (approximately 41 miles, north to south) and the corresponding watershed. The contributing basins include both the St. Lucie Watershed and the C-25 Basin, which together encompass more than 780 square miles (**Figure 3.1**). The western portion of the study area is predominantly agriculture with most urban areas located near the coast.

3.2 Existing Features and Hydrology

Much of the St. Lucie Watershed is traversed by agricultural drainage canals and ditches that discharge into the C-23, C-24, C-25, and C-44 Canals. The major canals extend from western portions of the watershed to discharge points on the St. Lucie River, St. Lucie Estuary, and the southern Indian River Lagoon.

The St. Lucie River is divided into the North Fork and South Fork. The North Fork Basin is in eastern St. Lucie and northeastern Martin Counties. The largest tributary to the North Fork is Ten Mile Creek, which drains 29,631 acres of agricultural and urban areas. This area is managed by the North St. Lucie River Water Control District, which is also responsible for controlling water releases from the Gordy Road Structure. The South Fork Subwatershed is about 49,965 acres in northeastern Martin County and the primary tributary is the C-44 Canal.

3.3 Hydrological Changes within the Watershed

The St. Lucie Estuary is the largest tributary to the southern Indian River Lagoon. Until the late 1800s, the estuary was the freshwater confluence of the North and South Forks of the St. Lucie River and provided freshwater inflow to the Indian River Lagoon. The construction of the St. Lucie Inlet near the mouth of the St. Lucie River permanently connected the lagoon to the Atlantic Ocean and changed the river to a riverine estuary.

Additional watershed and shoreline impacts have altered the character and health of the estuary and lagoon. The construction of an extensive network of canals began in the 1920s to promote agricultural and urban development through the removal of excess surface water and lowering water tables. The C-23, C-24, C-25, and C-44 Canals, built as part of the Central and Southern Florida Flood Control Project (see **Section 3.4**), rapidly drain their associated watersheds into the St. Lucie Estuary and the southern Indian River Lagoon. In addition, the C-44 Canal provides a route for Lake Okeechobee water to be discharged to the South Fork.

The canals have caused a loss of storage in the watershed that has increased stormwater runoff and altered the distribution of flows. The increased runoff has led to excessive freshwater discharges, which are further increased by regulatory releases from Lake Okeechobee, especially during wet periods. These excessive flows disrupt the natural magnitude and timing of freshwater deliveries to the estuary, resulting in salinity fluctuations that kill estuarine and marine organisms and degrade critical estuarine habitat (Haunert and Startzman 1985). The large amounts of fresh water entering the estuary also carry heavy nutrient loads leading to eutrophication, which causes algal blooms, low dissolved oxygen levels, fish lesions, and periodic fish kills (Chamberlain and Hayward 1996).

3.4 Project Goals and Objectives

The primary purpose of the Indian River Lagoon – South Project is to reduce the high volume freshwater discharges in the system. Restoring a more natural volume, timing, and distribution of flows to the estuary will give estuarine biota populations a better opportunity for recovery.

The Indian River Lagoon – South Project was authorized under the 1992 and 1996 Water Resources Development Acts, as part of the authorization for the Comprehensive Review Study of the Central and Southern Florida Project (Restudy)(USACE 1999). The Comprehensive Everglades Restoration Plan (CERP), which was part of the Restudy, includes numerous projects throughout the Kissimmee-Lake Okeechobee-Everglades connected watershed to improve these natural environments. In the Indian River Lagoon – South Project area, CERP recommends the construction of aboveground storage reservoirs to attenuate damaging freshwater discharges to the St. Lucie Estuary and southern Indian River Lagoon. The Water Resources Development Act (WRDA) of 2000 approved CERP as a framework to restore ecosystems in southern Florida and included specific authorization for the C-44 Basin Storage Reservoir in the southern St. Lucie Estuary drainage basin.

The Indian River Lagoon – South Project Implementation Report and Environmental Impact Statement recommends a project that supports the goals and objectives of CERP (**Table 3.1**) (USACE and SFWMD 2004). The purpose of the report, like CERP, was to investigate possible modifications to the Central and Southern Florida Flood Control Project, but at a much finer level of detail. The final project implementation report was authorized under the WRDA of 2007.

Table 3.1. Goals and Objectives of the Indian River Lagoon – South Project.

Goal: Restore Ecological Values

- Reestablish a natural pattern of freshwater flows to the St. Lucie Estuary and Indian River Lagoon
- Improve water quality in the St. Lucie Estuary and Indian River Lagoon
- Improve habitat for estuarine biota
- Increase spatial extent and functional quality of watershed wetlands
- Improve spatial extent and functional quality of native upland/wetland habitat
- Increase diversity and abundance of native plant and animal species, including threatened and endangered species

Goal: Restore Economic Values and Social Well Being

- Increase water supply
- Maintain existing flood protection
- Improve opportunities for tourism, recreation and environmental education
- Enhance commercial and recreational fisheries and associated industries

3.5 Project Features and Operational Strategy

One of the purposes of the Indian River Lagoon – South Project is to reduce damaging freshwater flows to the St. Lucie Estuary. Therefore, the final project implementation report was developed to capture, store, and attenuate high volume flows delivered to the estuary. However, to fully restore the St. Lucie Estuary, this project also involves redistributing freshwater flows to maintain a desirable salinity range within the estuarine system throughout the year.

The project implementation report consists of five features and operational modifications that together are expected to restore a more natural volume and location of freshwater deliveries, store more water on land, reduce excessive nutrient loads, restore natural water storage functions to terrestrial wetlands in the watershed, and restore water quality and more natural estuarine bottom communities. The five features include (1) reservoirs, (2) stormwater treatment areas, (3) natural storage and treatment areas, including restoration within the North Fork floodplain, (4) diversion, and (5) muck removal and the creation of artificial habitat within the estuary. **Figure 3.1** shows the general location of the major components of the project implementation report. The total initial cost of the project implementation report was estimated to be $1,207,288,000. The annual operation and maintenance costs were estimated at $6,145,000, including $1,954,500 for project monitoring (USACE and SFWMD 2004).

3.5.1 Reservoirs

The project implementation report calls for the construction and operation of four aboveground freshwater storage reservoirs, along with the necessary connecting canals, control structures, levees, and pumps, to provide 130,000 acre-feet of storage within the watershed. The four planned reservoirs are the C-44 Reservoir, C-23/C-24 North Reservoir, C-23/C-24 South Reservoir, and C-25 Reservoir. They will capture water from the C-44, C-23, C-24, and C-25 canals, thereby reducing the extreme peaks of freshwater discharge to the estuary. Though not designed specifically to reduce nutrient loads, these reservoirs are expected to reduce total phosphorus and total nitrogen loads by about 3 percent and reduce suspended sediment and muck deliveries to the estuary. The storage reservoirs would cover about 12,610 acres in Martin and St. Lucie Counties.

Water stored in the reservoirs would also be available to agriculture, which will reduce dependency on well water from the Floridan aquifer. Water stored in reservoirs should be lower in alkalinity and chloride concentration than water from the Floridan aquifer, which will make it a preferred water source for agricultural users.

3.5.2 Stormwater Treatment Areas

Four stormwater treatment areas will be built on 8,731 acres of existing agricultural and pasture land. They will be the C-44 Stormwater Treatment Area (East), C-44 Stormwater Treatment Area (West), C-23/C-24 Stormwater Treatment Area, and C-25 Stormwater Treatment Area. Their operation is expected to reduce sediment, phosphorus, and nitrogen deliveries to the estuary and allow for restoration of estuarine water quality. The recommended stormwater treatment areas would reduce phosphorus loads by up to 18 percent and nitrogen loads by up to 8 percent as compared to the expected 2050 Future without Project Condition. Construction and operation of the stormwater treatment areas in conjunction with the reservoirs is essential for delivering water of adequate quality for the restoration of this portion of the greater Everglades ecosystem.

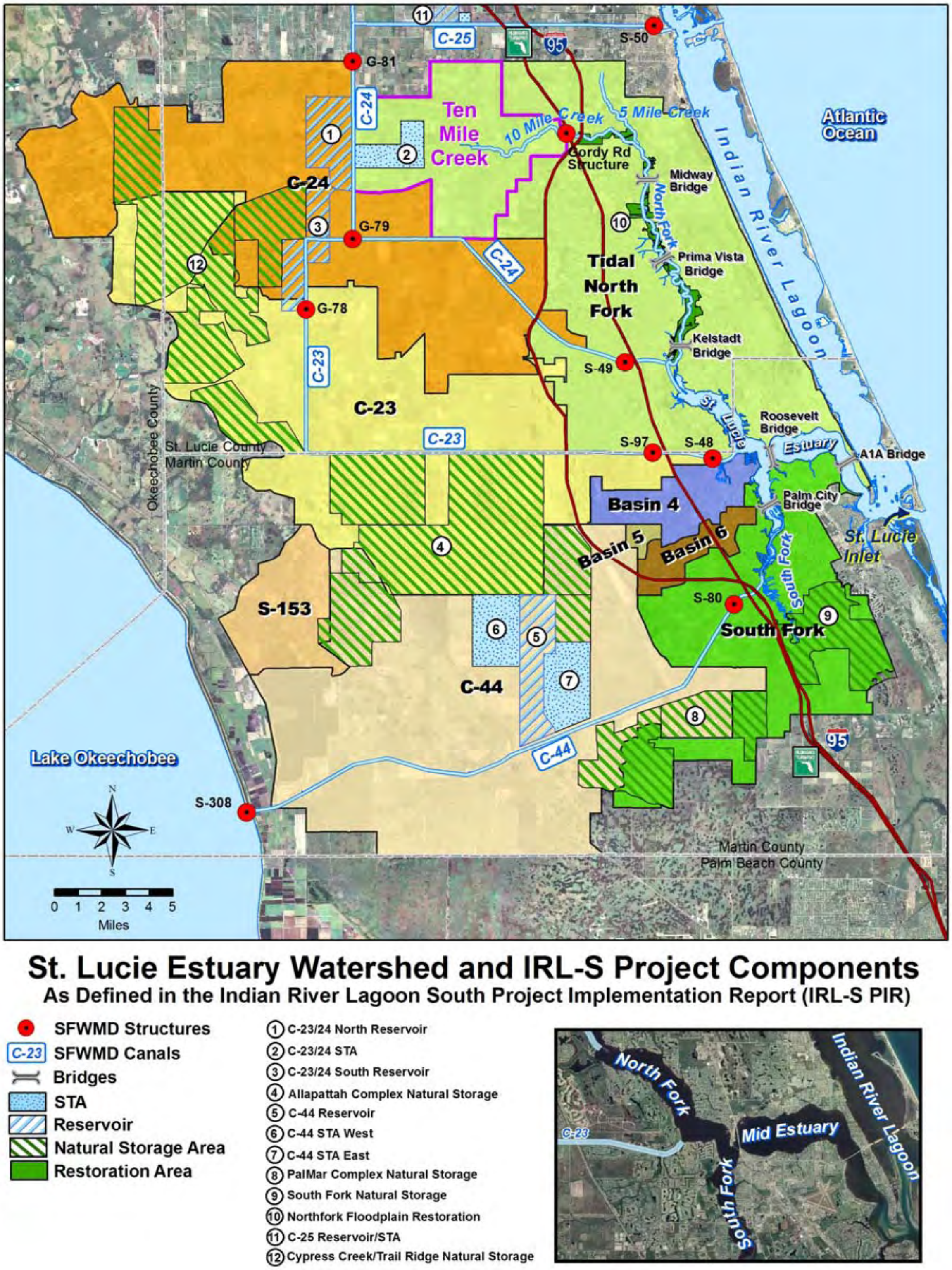

Figure 3.1. Major components of the Indian River Lagoon – South (IRL-S) Project as depicted in the project implementation report (USACE and SFWMD 2004).

3.5.3 Diversions

The diversion of existing flows via a canal connection and operating rules on new reservoirs and stormwater treatment areas will reduce the negative impacts of flows to the mid-estuary and provide for a more natural freshwater flow pattern in the North Fork of the St. Lucie River. Discharges from the C-24 outlet (S-49) will shift to the North Fork through the associated C-23/24 Stormwater Treatment Area outlet. This northerly diversion will direct approximately 64,500 acre-feet of water from the C-23 and C-24 Basins into the North Fork. Residual C-23 flows that are greater than the natural system flows through Basin 4 will be directed to the C-44 Reservoir, Stormwater Treatment Areas, and Canal via a proposed new canal before being discharged to the estuary through the S-80 Structure.

3.5.4 Natural Storage and Treatment Areas, North Fork Floodplain Restoration

Approximately 92,130 acres within the C-23, C-24, and C-44 Basins that have been disturbed by previous and current land use practices were identified in the project implementation report for acquisition and restoration. The planned natural storage and water quality areas are the Palmar Complex, Allapattah Complex, and Cypress Creek/Trail Ridge Complex. By restoring more natural hydrologic conditions through the modification of on-site drainage features, these natural lands are expected to provide approximately 30,000 acre-feet of storage within the watershed through retention in natural wetland systems. They are also expected to improve water quality by reducing the amount of nutrient loading due to large amounts of runoff.

Additionally, the project includes preserving approximately 3,100 acres of floodplain wetlands and oligohaline (low salinity) habitat within the North Fork of the St. Lucie River. Significant environmental improvement in the health of this portion of the river is expected to result from preventing degradation due to surrounding development. Preserving this portion of the river will provide additional water storage, maintain wading bird habitat, improve water quality, and protect areas that currently serve as a nursery area for larval and juvenile fish.

3.5.5 Muck Removal and Artificial Habitat

Removing 7.9 million cubic yards of muck from the North Fork, South Fork, and mid-estuary will provide immediate, and potentially dramatic, improvement in water quality, as well as improvements in habitat quality and extent. The recolonization process by targeted species within the estuary will be accelerated by depositing oyster shells, artificial reef balls, and artificial submerged aquatic vegetation in areas near the muck removal sites. These activities are expected to create another 90 acres of habitat.

The project implementation report recommends disposing the dredged materials at a permanent upland spoil disposal site. The site is located south of C-23 and west of the Florida Turnpike in Martin County. It has been under intense agricultural use for many years as a sod farm. The disposal site is one square mile in area and will be bounded by an approximately 18-foot high earthen levee. Dredged sediments will be pumped into the space and allowed to desiccate and consolidate in place.

3.6 Scope of Technical Analyses for Identifying Water to be Reserved

This analysis focuses on identifying water necessary for the protection of fish and wildlife that will be supplied by the construction and operation of 12,600 acres of new water storage reservoirs and 8,700 acres of new stormwater treatment areas, including the associated infrastructure (pumps, levees, and water control structures) necessary to capture, store, and attenuate high volume discharges to the St. Lucie Estuary and divert flows to benefit restoration of oligohaline habitat in the North Fork of the St. Lucie River, as outlined in the Indian River Lagoon – South Project Implementation Report and Environmental Impact Statement (USACE and SFWMD 2004). The project implementation report also recommended the acquisition of more than 92,000 acres of land within the watershed for the purpose of restoring the natural hydrology. The project implementation report identified water in the natural system associated with the natural storage and treatment areas to be protected by rule by the state. This will be accomplished under a future rule-making effort.

Section 4.
Description of the St. Lucie Watershed

4.1 Physiographic Setting

The St. Lucie Estuary and the North Fork of the St. Lucie River are located within a watershed that covers approximately 780 square miles within St. Lucie and Martin Counties, and a portion of Okeechobee County. Both of these water bodies are tributaries to the southern Indian River Lagoon and lie within the jurisdiction of the SFWMD. The physiography of the region has been described by White (1970), Clapp (1987), Glatzel and Da Costa (1988a, 1988b), Stauble (1988), and Nealon et al. (1987).

The St. Lucie Estuary is a drowned river valley formed by the confluence of two branches of the St. Lucie River, which accounts for it forked shape. The St. Lucie River is approximately 35 miles long and has two main branches, the North Fork and the South Fork (**Figure 4.1**). Both forks are relatively shallow. Water from the river's two forks flows into the North and South Forks of the estuary before mixing in the mid-estuary and moving into the lower estuary (**Figure 4.1**, inset). The North Fork estuarine area is about 4 miles long with a surface area of approximately 4.5 square miles. The South Fork is less than half the size of the North Fork with a surface area of about 1.9 square miles. During the 1920s, the South Fork was dredged to provide a navigable connection to Lake Okeechobee and is now part of the Okeechobee Waterway, which links the Atlantic Ocean and Gulf of Mexico. The mid-estuary is located between the North and South Forks (**Figure 4.1**) and represents the interface between freshwater and saltwater inputs into the estuary. The mid-estuary extends approximately 5 miles from the U.S. 1-Roosevelt Bridge to Hell's Gate Point and has an area of about 4.7 square miles (Haunert and Startzman 1985). The lower estuary is near the St. Lucie Inlet and is predominantly salt water depending on the tides.

The western portion of the watershed consists primarily of agricultural lands (citrus and pasture) while urban areas dominate the coastal areas. Municipalities within the watershed include the city of Fort Pierce, Port St. Lucie, St. Lucie Village, the city of Stuart, Sewall's Point, Jupiter Island, and Ocean Breeze Park.

The St. Lucie Estuary is the largest tributary to the southern Indian River Lagoon, is nationally recognized as part of the United States Environmental Protection Agency's National Estuary Program, and has been designated by the State of Florida as an Aquatic Preserve and Outstanding Florida Water. The Indian River Lagoon contains the greatest species diversity of any estuary in North America with approximately 2,200 species identified in the lagoon system. Thirty-five of the species are listed as threatened or endangered (Steward et al. 1994). Recognizing the importance of the estuary, the SFWMD established minimum flows and levels criteria for the North Fork in 2002 (SFWMD 2002).

The North Fork of the St. Lucie River also represents an important component of the Indian River Lagoon – South Project. A major goal of the project implementation report is to restore the river and its floodplain and provide a more natural quantity, quality, timing, and distribution of inflows to the estuary (USACE and SFWMD 2004).

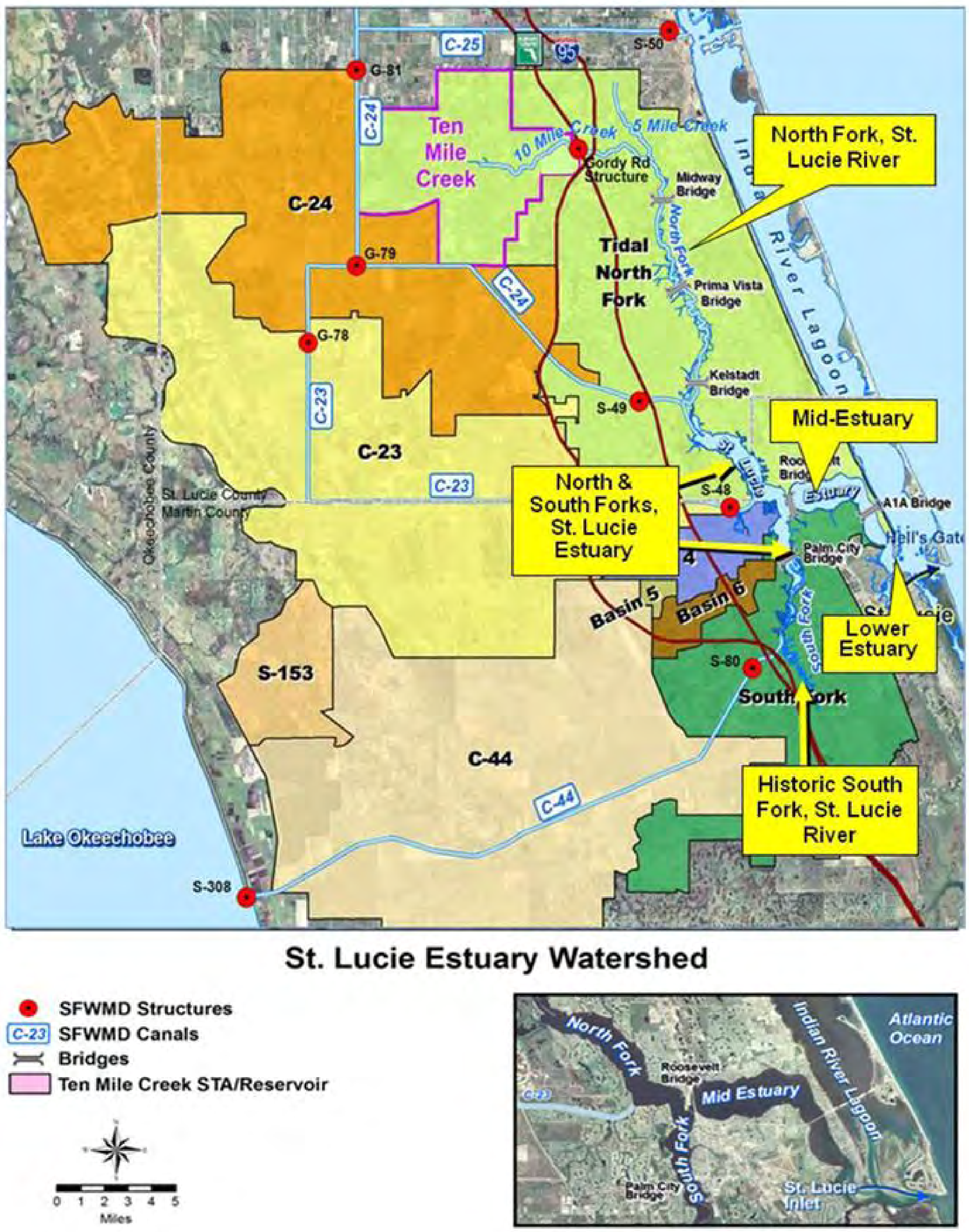

Figure 4.1. The St. Lucie Watershed, including primary basins and major water management canals and structures (SFWMD et al. 2008).

4.2 Description of the North Fork of the St. Lucie River

As explained in **Section 1**, this technical analysis focuses primarily on the North Fork of the St. Lucie River and the Ten Mile Creek Basin (Gordy Road Structure). The North Fork of the St. Lucie River (**Figure 4.2**) is located within northern Martin and southern St. Lucie Counties. A wide variety of fishes, turtles, birds, and marine mammals utilize the river and its floodplain as critical habitat. Mangroves, leatherfern, sawgrass, tidal marsh, and floodplain forest make up the primary plant communities along the river. The adjacent floodplain consists of natural islands and oxbows, as well as river corridors created through dredging. The river and floodplain support several protected species, such as the American alligator, manatees, river otters, nesting wood storks, little blue herons, brown pelicans, and opossum pipefish.

The river is approximately 17 miles long and contains open water, shoreline, and floodplain habitat. The lower portion of the river includes important low salinity habitat (salinities ranging from 0 to 10 practical salinity units [psu]) that provides a nursery area for larval and juvenile forms of estuarine and marine fishes. Gobies, sleepers, and pipefish are among the rare tropical fish species found in the North Fork and its headwaters (Gilmore 2007 [**Appendix E**]).

The North Fork of the St. Lucie River was historically a meandering, serpentine watercourse with an associated floodplain that drained an area considerably larger than today. However, in the early 1900s, portions of the North Fork were straightened and dredged to drain wetlands for agriculture and provide for flood control and navigation. Drainage and development has significantly altered the hydrology of the watershed, including the frequency of floodplain inundation, hydrodynamics, and salinity gradients. These hydrologic changes have dramatically changed the fish nursery function of the St. Lucie Estuary. Portions of the North Fork of the St. Lucie River now contain deep water habitats. Spoil from previous dredging projects was deposited along the newly created channel, causing adjacent wetlands to be hydrologically isolated from the river and closing oxbows that historically attenuated water flow south toward the St. Lucie Estuary. Initial hydrologic restoration plans for this area include reconnecting these oxbows and isolated wetland areas.

The North Fork of the St. Lucie River currently receives surface water runoff from Ten Mile Creek, the Tidal North Fork, and C-25 Basins (**Figure 4.1**). Inflows to the North Fork of the St. Lucie River are monitored at the Gordy Road Structure (river mile 32.35), located near the Florida Turnpike (**Figure 4.2**). Several miles downstream of this structure, Five Mile Creek contributes relatively limited inflows. Even further downstream, the C-24 Basin and S-49 Structure discharge to the southern portion of the North Fork of the St. Lucie River. Immediately downstream of the C-24 Canal, the river broadens dramatically and remains about 4,000 feet wide to the confluence of the North and South Forks of the estuary located at the U.S. 1-Roosevelt Bridge (**Figure 4.1**).

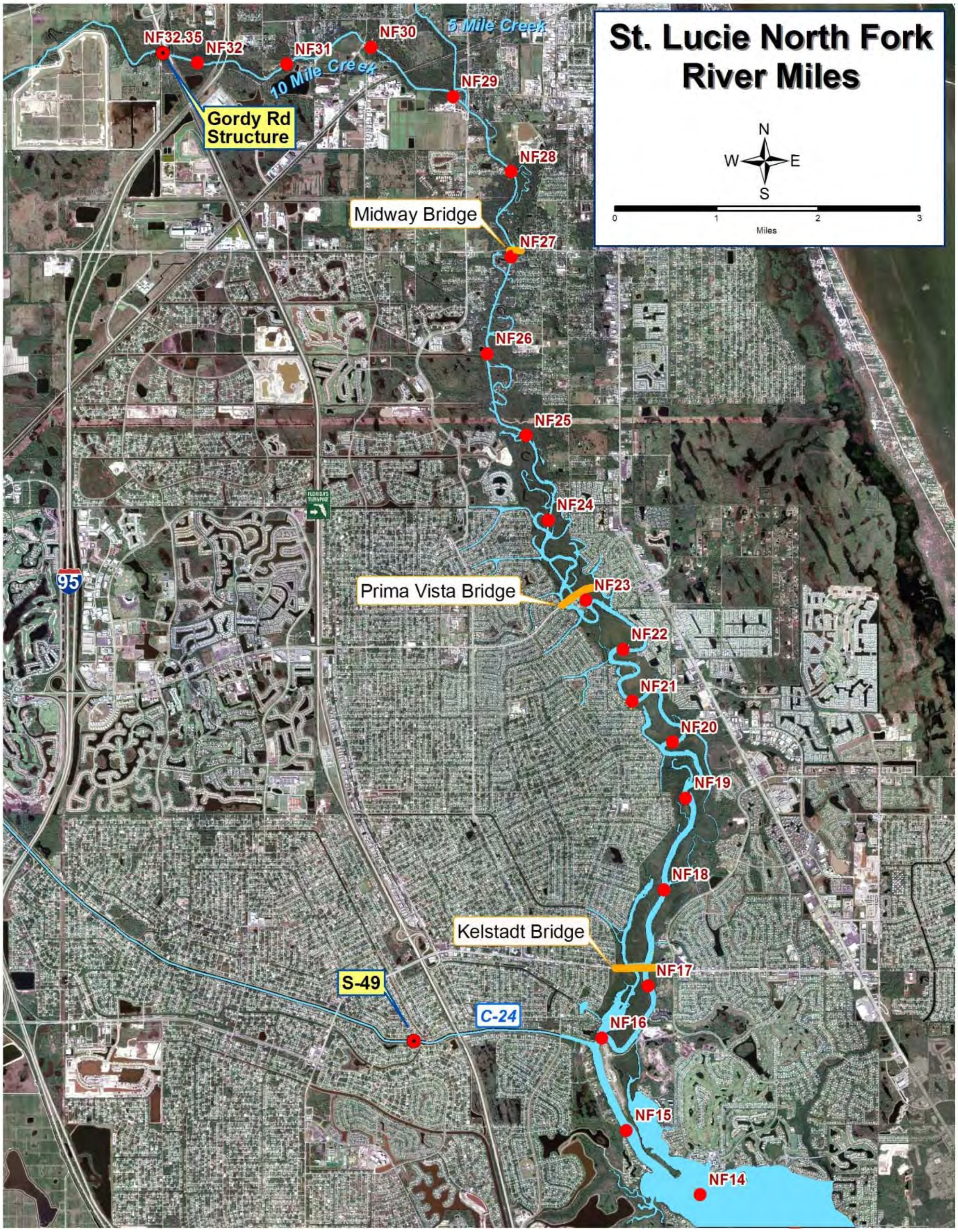

Figure 4.2. The North Fork of the St. Lucie River with North Fork (NF) river miles (red), water management structures (yellow), and geographic reference points (white boxes).

4.3 Climate

Rainfall patterns in South Florida resemble the wet and dry season patterns of the humid subtropics. On average, South Florida receives about 55 inches of rain each year and 70 percent of that typically falls during the wet season (June through October). Interannual extremes in rainfall result in frequent periods of flood and drought. Multiyear high and low rainfall periods often alternate (**Figure 4.3**). During the wet season, thunderstorms occur almost daily. Wet season rainfall generally follows a bimodal pattern with peaks during May–June and September–October. Tropical storms and hurricanes are major contributors to wet season rainfall and have a high level of interannual variability and a low level of predictability. During the dry season, rainfall is generally governed by large-scale winter weather fronts that pass through the region approximately weekly. High evapotranspiration rates in South Florida roughly equal mean annual precipitation.

For the St. Lucie Estuary Watershed, rainfall averaged 52.3 inches per year with a median value of 50.50 inches per year for the 41-year period of record (1965–2005). The lowest values occurred in 1981 (37.2 inches) and the highest in 1994 (76.6 inches) (**Figure 4.3** and **Appendix H**). Analysis of long-term rainfall records from the St. Lucie Estuary watershed indicates that the wet season can be defined as June 1 to October 31 and the dry season is from November 1 to May 31. These data were input into the St. Lucie Estuary Watershed Model (WaSh), as discussed in **Section 7** of this document.

Annual patterns of rainfall distribution within the St. Lucie Watershed were examined to determine the amount of rainfall typical of dry, normal, and wet conditions. Annual rainfalls for the period of record (1965–2005) were ranked using the rainfall data simulated by the South Florida Water Management Model (SFWMD 2005). Dry, normal, and wet years were selected as rankings near the 10 percent level (wet), 50 percent level (normal), and 90 percent level (dry) thresholds based on the 41-year rainfall distributions (**Appendix H**).

Results showed that annual rainfall total of 43.3 inches for year 1988 represented the 1-in-10 year drought condition (defined as the 90 percent threshold having a return period of about once every 10 years on average) for the St. Lucie Watershed. In contrast, 1966 annual rainfall inputs totaling about 64.3 inches represented the 10 percent threshold that defines the 1-in-10 wet year. Median or near normal rainfall inputs total about 50.5 inches, as represented by year 1996.

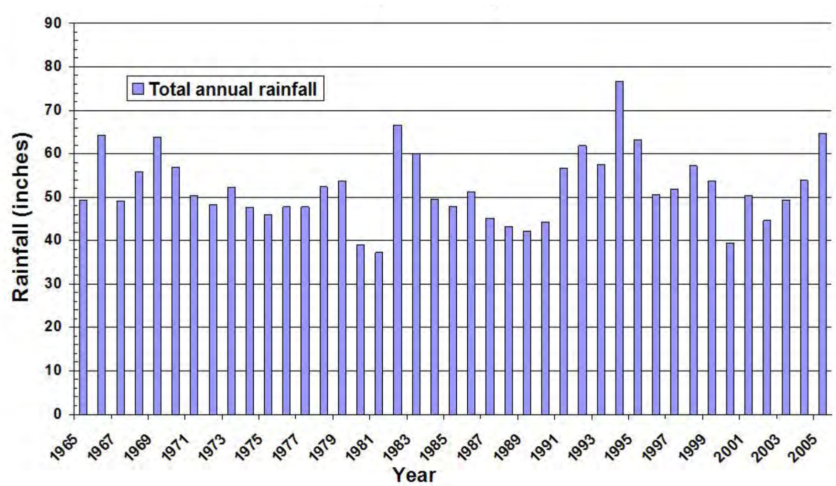

Figure 4.3. Annual rainfall inputs to the St. Lucie Watershed 1965–2005 (SFWMD 2005).

4.4 Geology and Soils

4.4.1 Geology

The Indian River Lagoon – South Project area includes coastal lowlands formed during the most recent ice ages. The relatively uniform soils and groundwater characteristics of the St. Lucie Watershed are a product of these periods of oceanic submergence and emergence.

The Indian River is a lagoon that separates the present day Atlantic Ocean barrier islands from the Florida peninsula mainland. The southern end of the lagoon intersects with the mouth of the St. Lucie Estuary and the St. Lucie Inlet. Historically, the estuary received water primarily from the North and South Forks of the St. Lucie River, which has the morphology of a typical “drowned river valley” formed by the rise in sea level during the last 7,000 years (Lee et al. 1997).

Uplands within the watershed have an average elevation of 28 feet in relation to the National Geodetic Vertical Datum of 1929 (ft NGVD 29) along the western boundary and are generally flat. Elevations within the study area range from 15 ft to 60 ft NGVD 29. The elevation of the coastal area between the Atlantic Ocean Barrier islands and the Atlantic Coastal Ridge ranges from 0 ft to 25 ft NVGD 29. The coastal sand hills of the Atlantic Coastal Ridge, adjacent to the Atlantic Intracoastal Waterway, are higher than most parts of the surrounding country.

4.4.2 Soils

Soils within the St. Lucie watershed can be grouped into five major categories: (1) soils of the sand ridges and coastal islands, (2) soils of low ridges and knolls, (3) soils of the flatwoods, (4) soils of sloughs and freshwater marshes, and (5) soils of the tidal swamps. The St. Lucie Watershed is dominated by pine flatwood, slough, and freshwater marsh soils. The remaining categories comprise minor soil associations that occur in riverbeds and other regions of major topographic change. Each individual soil can be further classified into a hydrological soil group based on surface water runoff or infiltration characteristics (Florida Soil Survey Staff 1992).

4.5 Major Aquifers

The Floridan aquifer is the largest in Florida. It is an artesian aquifer in the study area and an important source of irrigation water. Over 70 percent of the permitted irrigation acreage in St. Lucie and Martin Counties relies on the Floridan aquifer as a primary or backup source of water (SFWMD 1998). Water from the aquifer is highly mineralized in this region and requires reverse osmosis treatment for potable use.

The surficial aquifer system is the principal source of potable water within the study area. Its productivity varies both laterally and vertically. In general, the most productive areas are in the eastern portions of Martin and St. Lucie Counties and are not influenced by groundwater tables affected by the Central and Southern Florida Flood Control Project canals.

4.6 Land Use

The St. Lucie River Watershed includes much of Martin and St. Lucie Counties, and a small part of Okeechobee County. The drainage area measures more than 780 square miles. Agriculture is the dominant land use in the watershed (297,440 acres) (**Table 4.1**). The single largest land use is citrus, which encompasses 22.6 percent (116,442 acres) of the watershed. Improved pasture ranks second with 20.7 percent of the watershed (106,321 acres). Natural areas represent about 20.5 percent (105,380 acres) (SFWMD 2008a).

Developed residential and commercial centers are concentrated primarily within the eastern portion of the watershed (North Fork and South Fork Basins) near the St. Lucie River. Urban areas account for about 16.3 percent (83,861 acres) of the total area. In contrast, the western basins (C-44/S-153, C-23, and C-24) contain the largest amount of agriculture (**Table 4.1**).

Table 4.1. Current (2005) land use within the St. Lucie Watershed.

Land Use	Basins 4, 5 & 6	South Fork	C-24	C-23	**North Fork [1]**	C-44/S-153	Sub-Total	Percent
Residential Low density	4,316	3,330	1,236	1,909	9,445	1,814	22,050	4.3
Residential Medium Density	1,236	3,392	2,506	304	30,453	315	38,206	7.4
Residential High Density	703	1,730	295	0	4,784	186	7,698	1.5
Other Urban	1,151	3,026	783	1,385	8,974	588	15,907	3.1
TOTAL URBAN	**7,406**	**11,478**	**4,820**	**3,598**	**53,656**	**2,903**	**83,861**	**16.3**
Improved Pasture	1,007	9,552	33,950	33,628	4,999	23,185	106,321	20.7
Unimproved Pasture	86	1,094	6,064	5,062	558	2,168	15,032	2.9
Woodland Pasture/Rangeland	769	3,764	7,110	10,301	4,566	12,841	39,351	7.7
Row Crops	156	2,460	1,550	1,696	1,166	853	7,881	1.5
Sugar Cane	0	322	0	0	0	5,240	5,562	1.1
Citrus	30	3,025	17,488	32,466	20,678	42,755	116,442	22.6
Sod farms	0	0	0	0	0	294	294	0.1
Ornamentals	211	504	25	0	238	268	1,246	0.2
Horse Farms	54	71	14	54	0	592	785	0.2
Dairies	0	0	0	419	0	0	419	0.1
Other Areas	165	121	958	2,137	159	567	4,107	0.8
TOTAL AGRICULTURE	**2,478**	**20,913**	**67,159**	**85,763**	**32,364**	**88,763**	**297,440**	**57.8**
Water	383	1,791	1,218	1,811	4,317	1,891	11,411	2.2
NATURAL AREAS	**4,052**	**14,541**	**13,885**	**20,121**	**25,043**	**27,738**	**105,380**	**20.5**
Transportation	289	1,157	521	455	2,623	611	5,656	1.1
Communication/Uitlities	439	83	102	926	1,164	7,814	10,528	2.0
Totals	**15,047**	**49,963**	**87,705**	**112,674**	**119,167**	**129,720**	**514,276**	

1: In this analysis the North Fork includes both the Ten Mile Creek Basin and the Tidal North Fork Basins.

Other urban areas include commercial services, industrial, institutional, and recreational land uses.
Natural Areas include upland forests, wetlands, barren lands, and open lands.
Source: St. Lucie River Watershed Protection Plan (SFWMD 2008a)

4.7 Watershed Hydrology

4.7.1 Pre-drainage Hydrology

Until the late 1800s, the St. Lucie River was primarily fresh water with no permanent connection to the ocean. Natural inlets to the sea were only periodically open in the southern Indian River Lagoon. In 1892, increases in water and transportation demands led to the creation of a permanent inlet that connected the St. Lucie River and the Indian River Lagoon to the Atlantic Ocean. Tidal exchange transformed the once freshwater river into a brackish estuary (USACE and SFWMD 2004).

Historically, forests and natural wetland systems in the watershed held rainfall until it gradually percolated into the aquifer, evaporated, or flowed overland into tributaries. The northern tributaries, such as Ten Mile Creek, received most of the flow since the western watershed topography slopes northward and a coastal ridge (shown as the Green Ridge in **Figure 4.4**) acted as a barrier to flow to the central portion of the inner estuary. The cumulative flow from the natural watershed, which included the smaller South Fork tributaries, flowed into the St. Lucie River and provided fresh water to the Indian River Lagoon (Woodward-Clyde 1998).

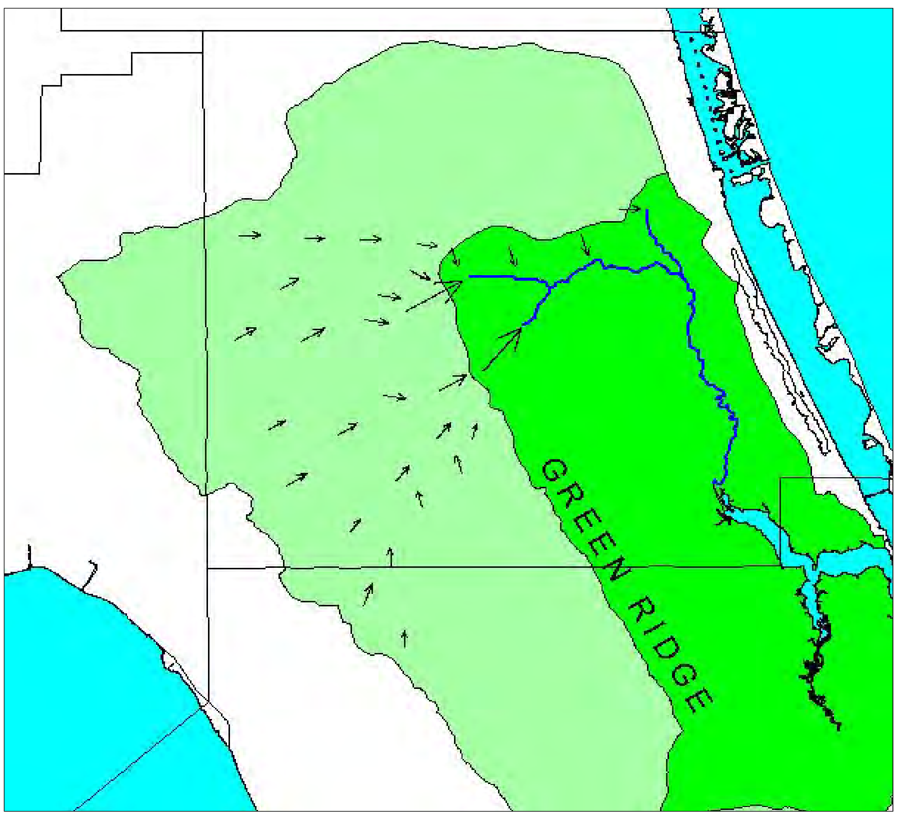

Figure 4.4. Historical flow patterns for the St. Lucie Estuary Watershed (VanZee 2001).

4.7.2 Drainage Alterations

Historical drainage patterns within the St. Lucie Watershed have been highly altered since the late 1800s (**Figure 4.5**). Continued population growth increased the demands for more land, better flood protection, and a dependable water supply. As a result of the disastrous hurricanes of 1946 and 1947, Congress authorized construction of the Herbert Hoover Dike around Lake Okeechobee to protect residents from flooding. To promote development, wetlands were drained to create residential land, cities, and agricultural fields.

From the 1920s to the 1950s, a high-density drainage conveyance system was created within the St. Lucie Watershed that allowed runoff to quickly enter the major drainage canals and downstream estuary. The watershed was enlarged when the North Fork was connected to the C-23/C-24 Canal system. Runoff from the North Fork drainage basins was diverted into canals (C-23, C-24) that cross the coastal ridge instead of being routed through the natural system. The C-24 Canal discharges to the lower portion of the North Fork of the St. Lucie River while the C-23 Canal drains into the St. Lucie Estuary at the confluence of the North and South Forks. The C-25 Canal, which is located north of the St. Lucie Watershed, drains into the Indian River Lagoon (**Figure 4.1**). The C-44/St. Lucie Canal connects Lake Okeechobee to the South Fork of the St. Lucie Estuary, providing a navigable link between the east and west coasts of Florida. The canal also made the St. Lucie Estuary one of the major outlets for water draining from the Upper Kissimmee and Lake Okeechobee basins. These major hydrologic modifications allow runoff to rapidly exit the watershed and discharge into the St. Lucie Estuary. Due to these changes, water from the St. Lucie Watershed is no longer detained, evaporated, cleansed, and attenuated in natural wetlands.

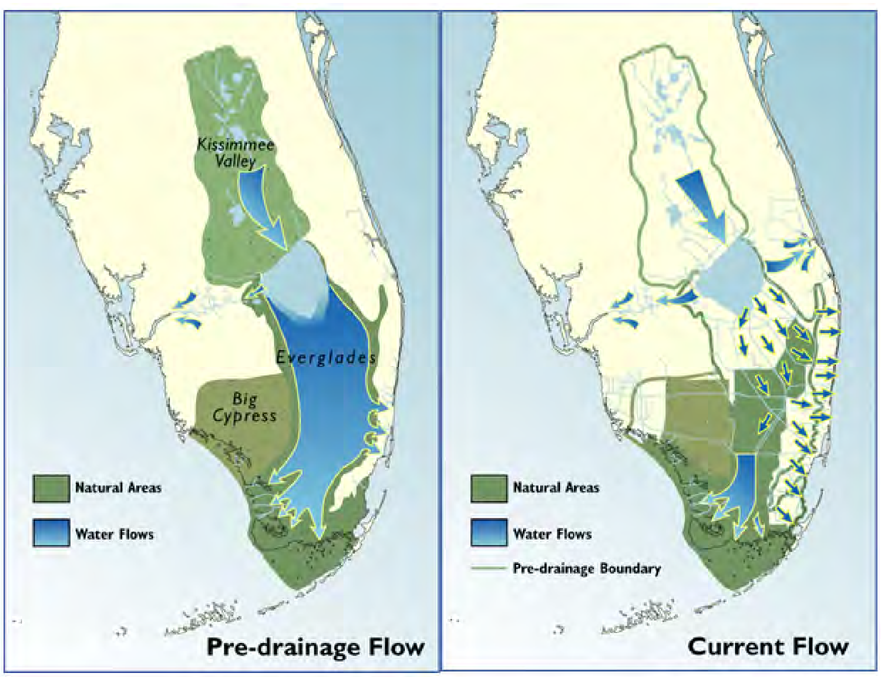

Figure 4.5. Historical and current Everglades system flow patterns.

4.7.3 Existing Hydrology

The St. Lucie Watershed now has an extensive set of large-scale primary, secondary, and tertiary canals and ditches intended to provide flood protection in the wet season and irrigation in the dry season. The drainage system also lowers the groundwater table to make more land useful for agriculture and urban development.

4.7.3.1 St. Lucie Watershed and Major Drainage Basins

The watershed consists of seven major basins (**Figure 4.1**). Four are controlled by major canals and water management structures (C) and the remaining three basins have basically uncontrolled outflows (U). These basins consist of the following:

- C-44 and S-153 Basins (C)
- C-23 Basin (C)
- C-24 Basin (C)
- Tidal North Fork Basin (U)
- Ten Mile Creek Basin (C)
- South Fork Basin (U)
- Basins 4, 5, and 6 (U)

Basin names typically coincide with the major drainage canal present within each basin. For example, the C-44 Canal is the major canal within the C-44 Basin. Drainage basins within the watershed are generally defined by topography and empty into a specific tributary or canal that connects to the St. Lucie Estuary.

C-44 and S-153 Basins

The C-44 and S-153 Basins are located in south-central Martin County and have a total drainage area of 129,719 acres (**Figure 4.1**). Land use in this area includes citrus farms (42,755 acres), pastures (38,810 acres), and natural areas (27,738 acres).

The C-44 Basin drains an area of 116,622 acres. The primary conveyance that serves this basin is the C-44 Canal, which has two control structures: the S-80 gated spillway (also known as the St. Lucie Lock and Spillway) and the S-308 gated spillway (also known as the Port Mayaca Lock and Spillway), which is on the eastern shore of Lake Okeechobee. The system removes excess waters from the C-44 Basin, supplies surface water to the C-44 Basin when needed, and maintains groundwater elevations sufficient to prevent saltwater intrusion. The C-44 Canal is also an integral part of the Okeechobee Waterway Navigational Project and, along with the Caloosahatchee River, provides a primary outlet from Lake Okeechobee for flood control. Water surface elevations in the C-44 Basin are regulated by S-80 and regulatory releases from Lake Okeechobee are made by way of S-308 (SFWMD 1988a, USACE and SFWMD 2004).

The S-153 Basin has a drainage area of 13,097 acres. The L-65 Borrow Canal within the basin is part of a continuous borrow canal along the east side of L-64 and L-65 that parallels the Florida East Coast Railway from C-44 to the railway's crossing of State Road 710. The only control structure in the basin is the S-153 gated spillway at the L-65 Borrow Canal's outlet to C-44, just north of Port Mayaca. The canal and control structure provide flood protection and drainage for the S-153 Basin by discharging excess water into C-44 and regulating surface water elevations. Water supply to the S-153 Basin is from local rainfall (SFWMD 1988a).

C-23 Basin

The C-23 Basin has a total drainage area of 112,675 acres (**Figure 4.1**). The majority of it is in southwest St. Lucie County and northern Martin County, with a small section in eastern Okeechobee County. Major land uses include pastures (47,387 acres), citrus (32,466 acres), and natural areas (20,121 acres).

The C-23 Canal provides most of the drainage in the basin. Water flows south from the intersection with the C-24 Canal to the Martin/St. Lucie County line, then heads east before discharging into the North Fork of the St. Lucie Estuary. There are three control structures in the C-23 Basin: S-48 (a fixed crest weir located at the outlet of the C-23 Canal to the North Fork of the St. Lucie Estuary), S-97 (a gated spillway located where the Florida Turnpike crosses the C-23 Canal), and G-78 (a culvert 3.6 miles southwest of where the C-23 and C-24 Canals join). The main functions of the canal and control structures in the C-23 Basin include removing excess water, supplying water to the C-23 and occasionally the C-24 Basin under low-flow conditions, and maintaining a groundwater table elevation west of S-48 sufficient to prevent saltwater intrusion into local groundwater. Water in the north-south leg of the C-23 Canal may occasionally be diverted north into the C-24 Basin for water supply and flood protection purposes (SFWMD 1988a).

C-24 Basin

The C-24 Basin has a total drainage area of approximately 87,706 acres and is located primarily within southwest St. Lucie County, with a small section in eastern Okeechobee County (**Figure 4.1**). Major land uses include pastures (46,904 acres), citrus farms (17,488 acres), and natural areas (13,885 acres).

The major drainage canals in the basin include the C-24 and a portion of the C-23. Four control structures regulate flow in the basin: S-49 (a gated spillway that controls water surface elevations in C-24 and controls discharges from C-24 to tide), G-78 (a gated culvert southwest of the confluence of C-23 and C-24), G-79 (a culvert in the alignment of C-23 at the intersection of C-23 and C-24 that controls flows east and west), and G-81 (a steel sheet-pile dam with a gated weir that divides the C-24 and C-25 Basins). The main functions of the canals and control structures in the C-24 Basin are to remove excess water, supply water, and maintain a groundwater table elevation west of S-49 to prevent saltwater intrusion into local groundwater. Water in the C-24 Canal can flow north to G-81, where it converges with the C-25 and flows east, or it can flow south to G-79 where it can continue east and discharge into the North Fork of the St. Lucie River or flow west and then south to the C-23 Canal (SFWMD 1988b, USACE and SFWMD 2004).

Tidal North Fork Basin

The Tidal North Fork Basin is in eastern St. Lucie and northeastern Martin Counties and comprises the North Fork and northern mid-estuary basins (**Figure 4.1**). The North Fork of the St. Lucie River bisects the basin and flows south and east about 17 miles to the St. Lucie Estuary, Indian River Lagoon, and ultimately to the Atlantic Ocean through the St. Lucie Inlet. The total drainage area of this basin is approximately 76,300 acres. Major land uses include urban areas, natural areas, and citrus farms.

The C-23A is a short section of canal in the lower reach of the North Fork of the St. Lucie River that passes discharges from the North Fork and C-24 Basins to the St. Lucie Estuary. Additionally, a short reach of the C-24 Canal extends from one mile west of Florida's Turnpike to the North Fork of the St. Lucie River. There are also several sub-basin tributaries within the Tidal North Fork Basin. Structure S-49 on the C-24 Canal is a gated spillway that controls surface water elevations in the canal and discharges from the canal to the North Fork of the St. Lucie River. The short reach of the C-24 Canal downstream of S-49 that is within this basin has no control structures and is tidally influenced. These canals, along with the S-49 Structure, regulate water levels in the Tidal North Fork Basin and the C-24 Basin (SFWMD 1988b).

Ten Mile Creek Basin

Ten Mile Creek is the largest tributary to the North Fork of the St. Lucie River (**Figure 4.1**). Water releases from Ten Mile Creek are regulated through the Gordy Road Structure, which is operated by the North St. Lucie Water Control District. The total drainage area of this basin is approximately 29,631 acres. Ten Mile Creek flows about 10 miles from the west to its confluence with Five Mile Creek. At this point the two creeks form the North Fork of the St. Lucie River.

Ten Mile Creek was channelized to promote drainage of surrounding agricultural lands. The plant communities along this creek have reestablished over time and are dominated by a mixture of wetland floating and emergent herbaceous species and by a fringe of transitional wetland/upland forest species. Surface water drainage from the Ten Mile Creek Basin has been diverted by an intricate canal system in the area that supports prime grapefruit production in St. Lucie County.

Basin boundaries for the Ten Mile Creek basin were determined based on the St. Lucie Watershed Assessment conducted by Coastal Environmental/Post, Buckley, Schuh & Jernigan for the District in 1999 (Janicki et al. 1999). These basin boundaries vary somewhat from the 298 District boundaries defined by the North St. Lucie River Water Control District along their northwest and southwest borders. These sub-basins have the ability to pump water west of the header canal to the C-24 and C-25 Basins for flood protection. Waters in these sub-basins are primarily retained in local canals for water supply during the dry season; while stormwater runoff is pumped into the C-24 and C-25 Basins during the wet season for drainage and flood control purposes.

South Fork Basin

The South Fork Basin drains an area of 49,965 acres (**Figure 4.1**) in northeastern Martin County to the east of the C-44 Basin. This basin includes the South Fork of the St. Lucie River from south of the Roosevelt Bridge, including the city of Stuart, to a portion of the area that is southwest and upstream of the S-80 Structure. Major land uses include natural areas (14,541 acres), pastures (14,410 acres), and urban areas (11,479 acres).

A continuation of the C-44 Canal is the only major drainage canal in the South Fork Basin. There are also eight sub-basin tributaries within the South Fork Basin. The only structure regulating flow in the South Fork Basin is S-80 (a gated spillway that restricts upstream and downstream stages and channel velocities to non-damaging levels), but no lands within this basin drain to the C-44 Canal upstream of the structure. Water can flow northeast along the C-44 Canal before discharging into the South Fork of the St. Lucie River southeast of the city of Stuart, or can flow west to Lake Okeechobee depending on the lake and canal stages (SFWMD 1988a).

Basins 4-5-6

Basins 4, 5, and 6 have a total drainage area of 15,055 acres in northeast Martin County (**Figure 4.1**). The predominant land uses are residential development (5,552 acres), natural areas (4,052 acres), and pastures (1,468 acres).

The C-23 Canal flows along the northeastern border of Basin 4 before draining into the St. Lucie Estuary. Basin 4 also includes the Bessey Creek and Hidden River tributaries, which flow into Basin 5 during periods of high tide. Basins 4 and 5 are commonly referred to as the Bessey Creek or Hidden River Basins. Basin 6 includes the Danforth Creek Tributary and is otherwise known as the Danforth Creek Basin. S-48 is the only control structure in Basins 4, 5, and 6. It is a fixed crest weir that controls surface water elevations in the C-23 Canal. The canal and S-48 Structure supply water to Basins 4, 5 and 6, remove excess water from the C-23 Basin, and prevent saltwater intrusion into groundwater.

4.7.3.2 Water Budget

A water budget representing existing hydrologic conditions within the St. Lucie Watershed is presented in **Table 4.2**. The water budget is based on measured historical rainfall and flow data taken from District water management structures (S-80, S-49, S-97, and Gordy Road) for 1965 to 2005 (the period of record). Missing values were augmented with data generated from the WaSh hydrologic model developed for the St. Lucie Watershed for current conditions (1965–2005). The WaSh model also provides estimates of daily inflows from ungauged basins such as the Tidal North Fork, South Fork, and Basins 4, 5 and 6. For more information on the use and application of the WaSh model in this project, see **Sections 5** and **7**.

Rainfall data were obtained from the South Florida Water Management Model database for 1965 to 2005 and were used as input data for the WaSh model (see **Section 4.3**). Twelve rainfall monitoring gauges were used to estimate rainfall inputs over the watershed. Missing data were interpolated from adjacent stations. These data represent the District's best available estimate of historical flows entering the St. Lucie Estuary from local watershed runoff.

Inflows to the estuary from Lake Okeechobee are not shown in the water budget analyses because releases from the lake are not addressed in this project. This assumption was also used as a given in the development of the Indian River Lagoon – South Project Implementation Report and Environmental Impact Statement (USACE and SFWMD 2004). Therefore, the water budget analysis is based on local watershed inputs only. Groundwater inputs to the estuary were not included in the above analysis due to the large uncertainty associated with this value. See **Section 7** of this report for a discussion of how groundwater was addressed in the District's hydrologic modeling of the estuary.

Together, the seven basins that comprise the watershed discharged an annual average of about 347,510 cubic feet per second (cfs) of runoff over the 41-year period of record (**Table 4.2**). This is equivalent to 689,285 acre-feet (ac-ft) of water per year. The Tidal North Fork Basin represented the largest contributor, providing 84,810 cfs or 24.4 percent of the flow delivered to the estuary. Other inputs included the C-23 Basin (20.2%), C-24 Basin (19.1%), C-44/S-153 Basins (14.3%), South Fork (11.0%), Ten Mile Creek through the Gordy Road Structure (6.5%), and Basins 4, 5 and 6 (4.1%) (**Figure 4.6**). The three "uncontrolled" basins (Tidal North Fork, South Fork, and Basins 4, 5 and 6) contribute about 39.5 percent of the total flow to the St. Lucie Estuary, while the three controlled outflow basins (C-44/S-153, C-23, C-24, and Ten Mile Creek) together contribute about 60.5 percent.

Table 4.2. Average annual inflows[1] delivered to St. Lucie Estuary for the 41-year period of record (1965–2005). Data based on measured historical flows with missing values augmented with data from the WaSh hydrologic model.

Sub-Watersheds	Structure	Average Annual Inflow (cfs)[3]	Average Annual Inflow (Acre-feet)	Average Daily Flow (cfs)	Percent Total Inflow	Rank
Tidal North Fork	UC[2]	84,810	168,220	232	24.4%	1
C-23 Basin	S-97	70,174	139,190	192	20.2	2
C-24 Basin	S-49	66,299	131,503	182	19.1	3
C-44/S-153 Basins	S-80	51,085	101,327	140	14.7	4
South Fork	UC[2]	38,210	75,790	105	11.0	5
Ten Mile Creek	Gordy Road	22,693	45,012	62	6.5	6
Basins 4, 5 & 6	UC[2]	14,239	28,243	39	4.1	7
Total Inflows[1]		347,510	689,285	951	100%	

1. Inflows from Lake Okeechobee and groundwater are not included
2. UC: uncontrolled inflow source
3. cfs: cubic feet per second

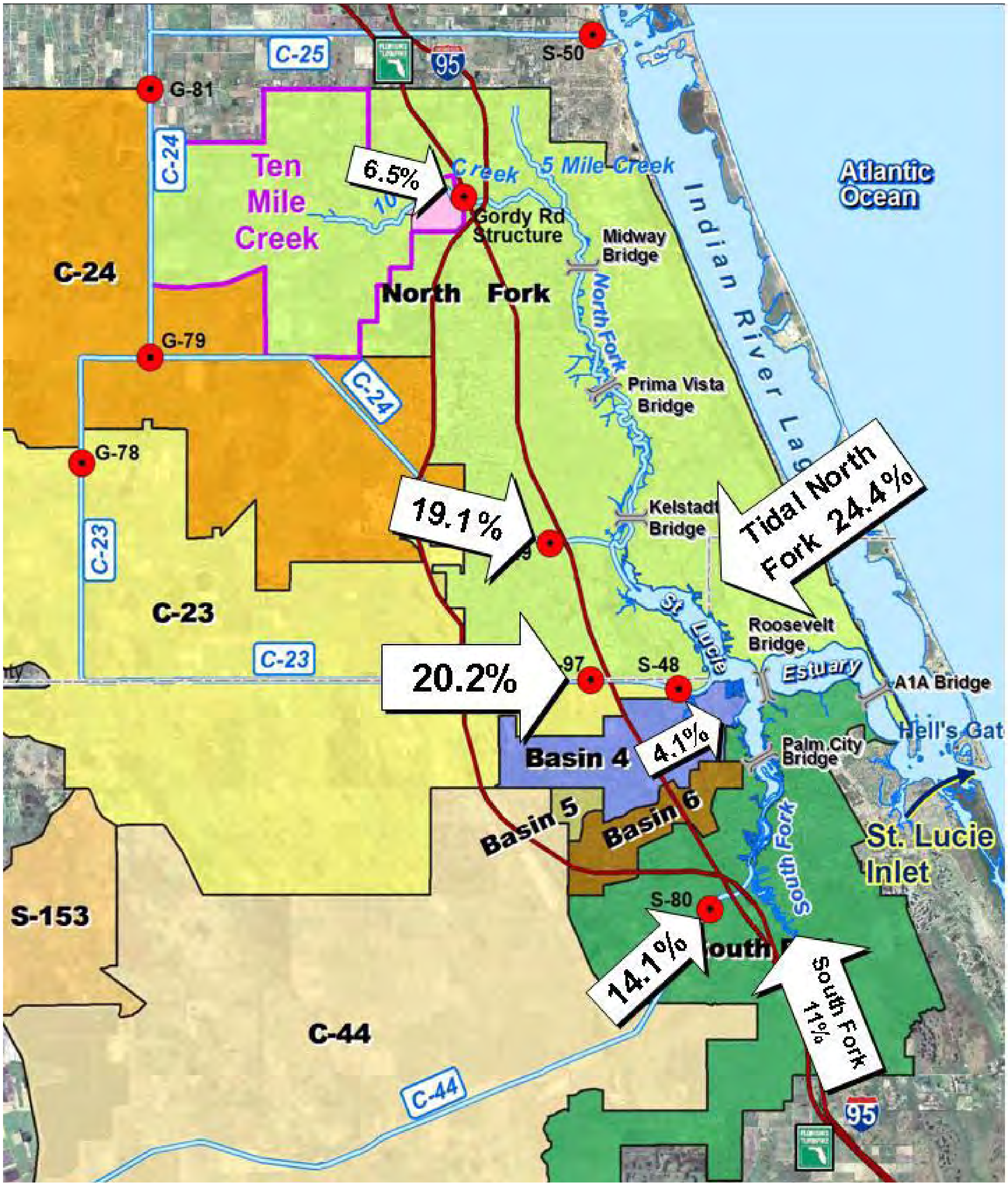

Figure 4.6. Relative annual contribution of major basins that provide freshwater inflows to the St. Lucie Estuary (average annual inflows representing existing conditions).

4.7.3.3 Water Demands and Sources

Land use within the watershed is predominantly agriculture and is expected to remain so in the future (**Table 4.3**). Citrus is by far the dominant irrigated crop and occupies over 40 percent of the irrigated agricultural acreage in the region. Agricultural irrigation primarily uses surface water and is supplemented with water from the Floridan aquifer system when surface sources are low (USACE and SFWMD 2004).

Updated water demand projections for the Upper East Coast Planning Area (Martin, St. Lucie, and Okeechobee Counties) show agricultural water demands decreasing by 7 percent from 2000 to 2025, while public water demands are anticipated to increase by 179 percent. Total water demands in the region are projected to increase 30 percent by 2025 (**Table 4.3**) (SFWMD 2006).

For agricultural irrigation, predominately citrus, a combination of surface water from the C-23, C-24, C-25, and C-44 Canals, supplemented with Floridan aquifer water, will be relied upon to meet existing and future needs. Since economic conditions in the citrus industry have changed, previous projections of increases in irrigated agricultural acreage have recently been reassessed. Growth in overall agricultural demand from 2000 levels is not anticipated (SFWMD 2006).

The Upper East Coast Planning Area's projected population growth over the next 20 years will significantly impact the region's public water demands, particularly in the urban sector. The region's total population is expected to increase from 320,664 in 2000 to about 584,927 residents by 2025. Most coastal public water supply utilities have begun transitioning to the Floridan aquifer in addition to continued use of this water source by the citrus industry. In 2000, the use of the Floridan aquifer by utilities accounted for 20 percent of the total utilities withdrawal in the Upper East Coast Planning Area, which is greater than usage in 1998 (**Table 4.4**). This trend is anticipated to continue as most of public water supply utilities in the region plan their future use to be supplied by the Floridan aquifer. The utilities in the area that use, or are developing the Floridan aquifer for future demands, include South Martin Regional, Martin County North, Martin County Tropical Farms, Port St. Lucie, and Fort Pierce Utilities Authority. In some areas of the region, utilities have decreased surficial aquifer withdrawals with development of the Floridan aquifer (SFWMD 2006).

Table 4.3. Overall water demands for the Upper East Coast Planning Area for 2000 and 2025.

Water Use Category	Est. Historical Demands 2000[1]	Projected Average Year Demands 2025[1]	Percent Change
Agriculture[2]	212.8	197.1	-7
Public Water Supply	36.5	101.9	179
Domestic Self Supply	14.6	2.7	-82
Commercial and Industrial Self Supply	3.3	4.9	48
Recreational Self Supply	12.8	23.8	86
Thermoelectric Power Generation Self Supply	9.8	47.6	386
Totals	**289.8**	**378.0**	**30.4**

1. Units are million gallons per day (MGD).
2. Agricultural demand projections do not include approximately 23,000 acres of citrus land coming out of irrigated citrus production with implementation of the Indian River Lagoon – South Project (SFWMD 2006).

Table 4.4. Public water supply water sources and use, 1998–2000.

	1998	1999	2000
Floridan Aquifer			
Total	5.09	6.57	8.48
% of Total	16%	18%	20%
Surficial Aquifer			
Total	27.28	30.52	34.72
% of Total	84%	82%	80%
Total Use	**32.37**	**37.09**	**43.20**

Units are million gallons per day (MGD)
(Source: SFWMD 2006)

4.8 Water Quality

4.8.1 Effects of Watershed and Land Use Changes

Evidence from sediment cores shows that over time, the St. Lucie Estuary has alternated between being fresh water or estuarine (Schrader 1984). Natural inlets to the sea were only periodically open in the southern Indian River Lagoon and there was no permanent connection with Lake Okeechobee. Rainfall within the watershed gradually percolated into the underground aquifer, evaporated, or flowed overland into tributaries. This changed in 1892 when the St. Lucie Inlet was excavated to provide navigational access to the ocean. The existence of the inlet also allowed tidal exchange, which has transformed the once freshwater St. Lucie River into an estuary.

Canal construction in the watershed has greatly changed how water flows through the area. The C-44 Canal, which connects Lake Okeechobee to the South Fork of the St. Lucie Estuary, was completed in 1928. Completion of the canal provided a navigable connection between the east and west coasts of Florida and also made the St. Lucie Estuary a major outlet for water draining from the Upper Kissimmee and Lake Okeechobee Basins. Extensive local agricultural drainage canal systems were constructed within the watershed beginning in the 1920s. During the 1950s, the watershed was significantly enlarged when the North Fork of the St. Lucie Estuary was connected to the C-23/C-24 canal system as part of the Central and Southern Florida Flood Control Project. Watershed runoff from the North Fork drainage basins was diverted into these canals that cross the coastal ridge instead of being detained, evaporated, cleansed, and attenuated in natural areas. The 780 square mile watershed now has an extensive array of primary, secondary, and tertiary canals and ditches that provides flood protection in the wet season and irrigation in the dry season. This combination of enhanced drainage within the watershed, flood control releases from Lake Okeechobee, population growth, and urban and agricultural development have impacted the quality of water discharged from the watershed to the North Fork of the St. Lucie River and the downstream estuary.

The St. Lucie River Watershed Protection Plan (SFWMD 2008a) identified three major influences that affect the estuary’s ecological health: (1) excessive nutrient loading from urban runoff, fertilizers, agricultural operations and septic systems; (2) local freshwater discharges from the St. Lucie River watershed; and (3) regulatory releases from Lake Okeechobee that cause rapid and prolonged salinity decreases within the estuary. These influences have caused changes in salinity, dissolved oxygen content, turbidity, and other water quality factors within the estuary.

Land use changes and drainage practices have contributed to elevated nutrient concentrations within the watershed. Agriculture, primarily citrus and pasture, dominates land use in the C-23 and C-24 Basins and accounts for about 76 percent of land area. Natural areas account for about 15.8 percent of the C-24 Basin and 17.8 percent of the C-23 Basin. Urban land use is only about 3 to 5 percent in these two basins (**Table 4.1**). In the C-44 Basin, land use is about 2 percent urban and 58 percent agriculture. In contrast, the Ten Mile Creek and Tidal North Fork basins represent highly urbanized areas (45 percent) with some agriculture (27 percent) and natural areas (21 percent) present (**Table 4.1**).

4.8.2 Water Quality Monitoring Programs

The District currently operates two water quality monitoring programs in the proposed reservation area. The St. Lucie Tributary Monitoring Program is a short-term monitoring program for some of the smaller tributaries that drain to the river and estuary. It is designed to measure the effectiveness of best management practices, support adaptive management, and measure tributary loadings. In contrast, the St. Lucie Estuary Water Quality Monitoring Program is a long-term effort that measures flow and water quality at major control structures that discharge to the estuary. This program was established in 1990 to detect long-term spatial and temporal trends within the estuary and includes multiple water quality parameters. It is considered sufficient to measure progress towards meeting water quality targets or concentrations resulting from nutrient load reductions. Data is collected monthly, which is adequate to quantify long-term trends but could miss episodic events, such as algal blooms (SFWMD 2008a). **Figure 4.7** provides a map of existing water quality monitoring sites within the St. Lucie Estuary and North Fork of the St. Lucie River.

In addition to water quality monitoring, salinity and bacteria monitoring programs are in place that measure these factors at key locations. The salinity monitoring program supports the District's water quality modeling efforts, helps refine salinity targets, and helps quantify the goal of reducing undesirable salinity levels within the estuary and river. A long-term tide and salinity monitoring network was established within the St. Lucie Estuary in 1997. All tide and salinity monitoring stations take water level, temperature, and conductivity measurements at 15-minute intervals. The current monitoring plan is sufficient for basic salinity monitoring needs (SFWMD 2008a).

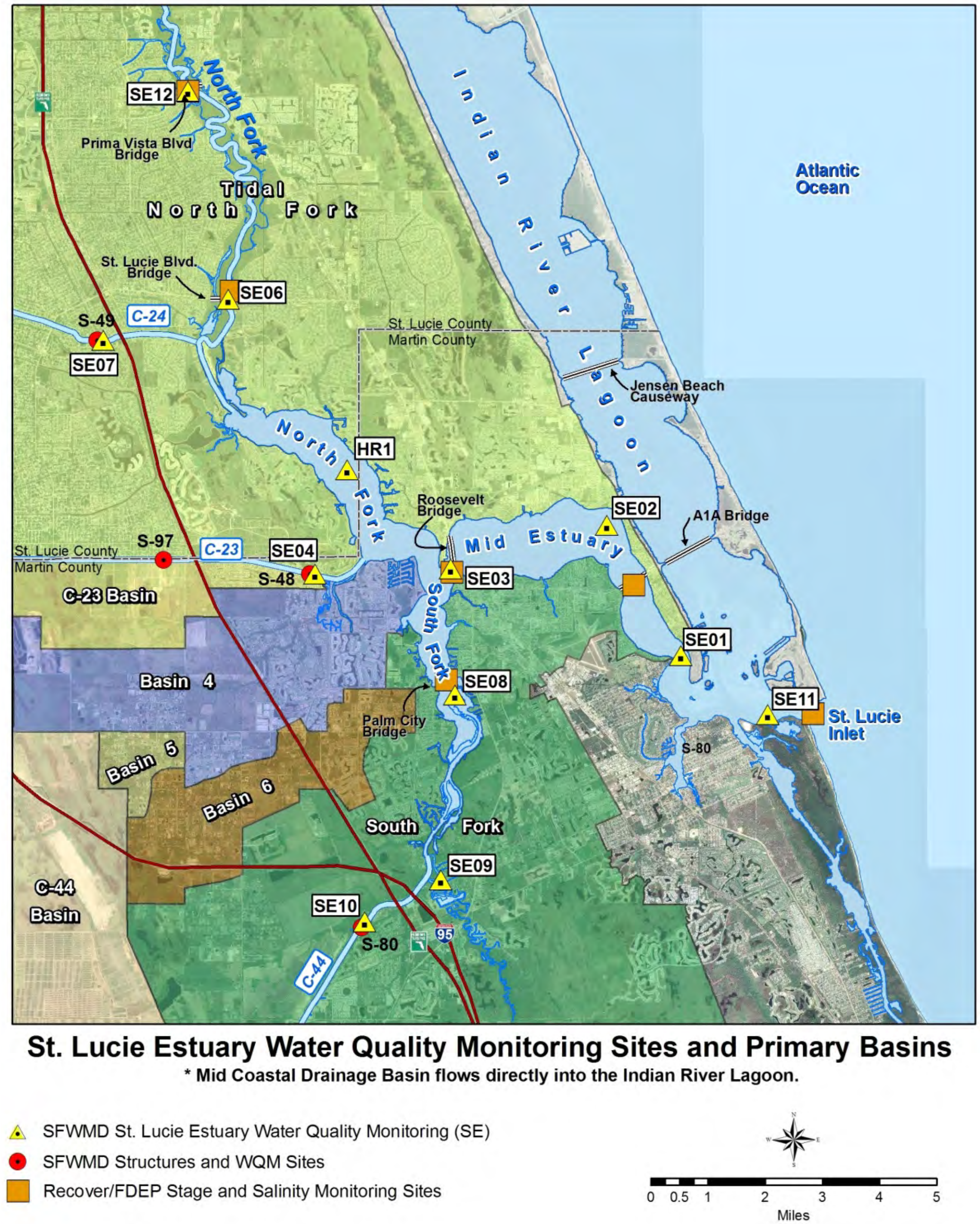

Figure 4.7. St. Lucie Estuary water quality monitoring sites.

4.8.3 Water Quality Trends and Status

Most surface waters in the St. Lucie watershed are designated Class III waters, as defined in Rule 62-302.400 F.A.C., with a designated use for recreation and the propagation and maintenance of a healthy, well-balanced population of fish and wildlife. Other waters in the watershed are secondary and tertiary canals located in agricultural areas and are Class IV waters, which means they are used for agricultural water supply.

The St. Lucie River Watershed Protection Plan (SFWMD 2008a) provides the following summary of existing water quality trends within the watershed and downstream estuary:

1) Low dissolved oxygen conditions in the St. Lucie River Watershed occur primarily during the wet season due to increased watershed runoff, high temperatures, elevated nutrient levels, and enhanced primary productivity.
2) Concentrations of most water quality parameters within the St. Lucie Estuary generally decrease from west to east as a result of nutrient-laden freshwater discharged to the North and South Forks of the St. Lucie Estuary.
3) Low dissolved oxygen is likely a result of salinity stratification in some areas and some monitoring stations have recorded values below the U.S. Environmental Protection Agency standards more than 20 percent of the time over the last decade. Stratification tends to occur during wet events.
4) Salinity varies on daily, monthly, seasonal, and annual time scales, as is true for many estuaries because their levels are driven primarily by rainfall and freshwater inflow. Salinity is higher during the dry season, due to less freshwater runoff from the upstream basins.
5) Nutrient loading rates are controlled by both discharge rates (flow) and nutrient concentrations. A strong correlation exists between nutrient concentrations in runoff and land use. Regressions between total annual flow and annual loadings show that annual loading is largely controlled by flow, which explains about 81 percent of loading variation for both total nitrogen and total phosphorus.
6) Average nutrient loadings to the estuary were 2,218 metric tons per year for total nitrogen and 373 metric tons per year for total phosphorus from 1995 to 2005. The annual loadings varied in response to rainfall. The wettest years (1995, 2004, and 2005) averaged 4,000 metric tons for total nitrogen and 600 metric tons for total phosphorus. Discharges from Lake Okeechobee played a significant role in nutrient loading during wet years. In contrast, for dry years such as 1996, 1997, and 2000, annual loading estimates were only 1,000 metric tons for total nitrogen and 100 to 170 metric tons for total phosphorus (SFWMD 2008a).

4.8.4 Water Quality Management Programs

4.8.4.1 Total Maximum Daily Loads Program

A recent water quality assessment of the St. Lucie River Watershed, adopted by the Florida Department of Environmental Protection on March 26, 2009, for the development of Total Maximum Daily Loads, indicates that the various basins and water bodies within the watershed are impaired in terms of low dissolved oxygen, high nutrients (nitrogen and phosphorus), and high biological oxygen demand (Parmer et al. 2008). Total Maximum Daily Loads establish the maximum amount of a pollutant that a water body can assimilate without causing exceedances of water quality standards.

Table 4.5 and **Figure 4.8** identify those basins (water bodies) within the St. Lucie Watershed that have been determined by the FDEP as impaired for either nutrients or dissolved oxygen based on data collected from 1996 to 2005. These basins have been verified as impaired for nutrients based on annual chlorophyll *a* data that exceeds 20 micrograms per liter (µg/L) in freshwater segments and 11 µg/L for marine waters, which are the threshold values that the FDEP uses to implement the narrative nutrient criteria (Section 62-302, F.A.C.). Each water body shown in **Figure 4.8** was verified as impaired for dissolved oxygen if the data showed that oxygen levels were below state standards more than 10 percent of the time. Surface waters within the St. Lucie River Basin are designated as Class III water bodies. The Class III water quality criterion for dissolved oxygen in fresh water is not less than 5.0 milligrams per liter (mg/L). For marine water bodies, dissolved oxygen levels shall not average less than 5.0 mg/L in a 24-hour period and shall never be less than 4.0 mg/L (Parmer et al. 2008).

Table 4.5 shows that the North Fork of the St. Lucie River is impaired in terms of high biological demand and high total phosphorus. Dissolved oxygen concentrations within this basin routinely fall below 5.0 mg/L and appear linked to high total phosphorus levels. In contrast, the North Fork of the St. Lucie Estuary was found to be impaired as a result of high total nitrogen levels. The C-23 and C-24 Canals were identified as impaired for nutrients and dissolved oxygen. These two canals transport loads of nutrients and eroded sediment to the estuary with slugs of fresh water that create wide salinity fluctuations within the estuary. The C-44 Canal was identified as impaired with respect to high biological oxygen demand; while the South Fork of the St. Lucie River and Bessie Creek were impaired due to high total nitrogen concentrations. The only basins identified in the FDEP report as not impaired were the (Coastal) St. Lucie River Lower Estuary and the South Fork of the St. Lucie Estuary (Parmer et al. 2008).

Table 4.5. FDEP Impaired Waters Rule listed water body information (Parmer et al. 2008).

Planning Unit	Water Body	WBID	Impairment Status & Details	
			Dissolved Oxygen	Nutrients
Coastal	St. Lucie River Lower Estuary	3193	Not Impaired	Impaired
North St. Lucie	North Fork St. Lucie River	3194	Impaired; linked to high TP and BOD	Impaired
North St. Lucie	North St. Lucie Estuary	3194B	Impaired; linked to high TN	Impaired
C-24	C-24	3197	Impaired; linked to high TP and BOD	Impaired
C-23	C-23		Impaired; linked to high TP	Impaired
South St. Lucie	South Fork, St. Lucie Estuary	3210	Not impaired	
South St. Lucie	South Fork, St. Lucie River	3210A	Impaired; linked to high TN	Impaired
South St. Lucie	Bessey Creek	3211	Impaired; linked to high TP	Impaired
C-44	C-44	3218	Impaired; linked to high BOD	Not impaired

WBID: FDEP water body identification units
BOD: biological oxygen demand
TP: total phosphorus
TN: total nitrogen

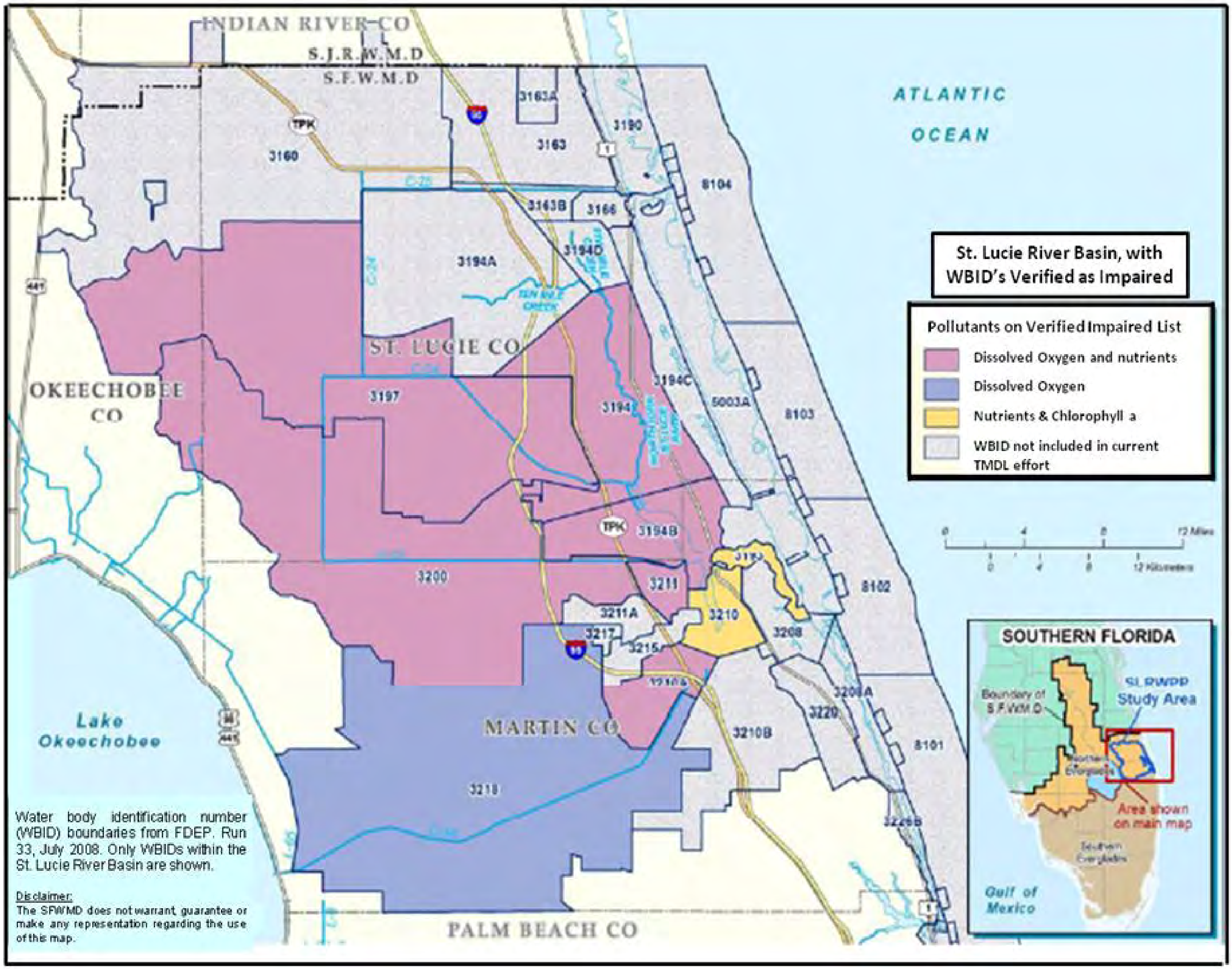

Figure 4.8. Water bodies within the St. Lucie Estuary Watershed classified by the FDEP as impaired (Parmer et al. 2008).

4.8.4.2 St. Lucie River Watershed Protection Plan

The St. Lucie River Watershed Protection Plan was developed by the District in cooperation with the FDEP, the Florida Department of Agriculture and Consumer Services, Martin and St. Lucie Counties, and affected municipalities (SFWMD 2008a). The watershed protection plan first reviewed water quality improvement programs and projects under consideration within the watershed (e.g., CERP Indian River Lagoon – South Project) and determined their expected cumulative benefits. These benefits were then compared to the identified objectives of the watershed protection plans to determine if any gaps existed and whether additional projects or programs would be necessary. Key objectives of the watershed protection plan were to:

- Reduce nutrient loads delivered from the watershed to meet any future adopted Total Maximum Daily Loads being developed by the FDEP
- Reducing the frequency and duration of undesirable salinity fluctuations in the estuary while meeting other water-related needs such as water supply and flood protection

A set of four alternatives were developed and were evaluated for nitrogen and phosphorus load removal and water quantity performance. The resulting plan combined the Watershed Construction Project, Watershed Pollutant Control Program, and Watershed Research and Water Quality Monitoring Program into a comprehensive approach that best met legislative goals.

The St. Lucie Watershed Protection Plan identified the best combination of watershed storage projects and water quality projects needed to help improve the quality, timing, and distribution of water in the natural ecosystem. The plan includes those projects identified as part of the Indian River Lagoon – South Project Implementation Report (USACE and SFWMD 2004), best management practices and regulatory programs, additional regional phosphorus treatment within the C-23/24 Basins, and local water quality and quantity projects.

Working in concert with the Lake Okeechobee Watershed Construction Project Phase II Technical Plan (SFWMD 2008b), expected results of the St. Lucie River Watershed Protection Plan include:

- Implementation of best management practices on more than 297,000 acres of agricultural lands and on nearly 84,000 acres of urban lands
- Completion of proposed regulatory rule revisions
- Construction of reservoirs and stormwater treatment areas
- Reduction of total phosphorus loads to the St. Lucie Estuary by 55 percent and total nitrogen loads by 56 percent
- Restoration of approximately 95,000 acres of wetlands and natural areas within the St. Lucie River Watershed
- Removal of more than 8 million cubic yards of muck sediment from the St. Lucie Estuary
- Provision of approximately 200,000 acre-feet of water storage within the St. Lucie River Watershed (in addition to 900,000 acre-feet of identified storage needs in the Lake Okeechobee watershed)

The watershed protection plan also includes recommendations to continue existing estuarine and watershed monitoring programs and to initiate four additional applied research projects to track progress towards achieving the plan’s objectives. Total phosphorus and total nitrogen load reduction performance will be revisited once the Total Maximum Daily Loads are formally adopted by the FDEP, which will provide specific loading rates, compliance locations, and compliance methodology (SFWMD 2008a).

4.9 Biological Communities

The variety of habitats within the Indian River Lagoon, the St. Lucie Estuary, and their watersheds supports the greatest species diversity in North America. Swain et al. (1994) identified more than 4,300 plant and animal species directly associated with the Indian River Lagoon. However, key organisms used to monitor the overall health of an estuary, such as oysters and submerged aquatic vegetation communities, currently exist in extremely low numbers within the estuary. Their scarcity suggests that the ecosystem is under stress. Degradation or loss of these communities directly affects the base of the St. Lucie Estuary food web, impacting upper trophic level organisms. Declines in oyster and aquatic vegetation communities also affect the economic base of the study area, which is dependent upon sustaining healthy populations of fish and wildlife. These impacts are especially significant following large releases of flood control discharges from Lake Okeechobee and the surrounding watershed to the estuary. In addition, shifts in natural habitats, such as the loss of functional wetlands and conversion of native pine flatwoods to citrus have also adversely affected ecological conditions within the watershed.

4.9.1 Plant Communities

A wide array of plant communities, both aquatic and terrestrial, provides the basis for the overall species diversity in the area. Virnstein and Cairns (1986) identified seven species of submerged aquatic vegetation in the Indian River Lagoon, though more recent studies found only four: shoal grass (*Halodule wrightii*), widgeon grass (*Ruppia maritima*), Johnson's seagrass (*Halophila johnsonii*), and wild celery (*Vallisneria americana*) (URS 1999). The submerged aquatic vegetation found during the survey was so sparse that only point locations, and not beds, could be mapped. Very sparse submerged vegetation cover, mainly shoal grass, was found in the lower estuary. No submerged vegetation was documented in the mid-estuary or in the North Fork and only small patches were found in the South Fork. Very sparse Johnson seagrass communities were found within the lower estuary. The reader is referred to Section 3.5.1 of the Indian River Lagoon – South Project Implementation Report (USACE and SFWMD 2004) for more details regarding the historical and present-day distribution of seagrass communities within the Indian River Lagoon.

The watershed includes five major upland vegetation types: pine flatwoods, scrub forest, cypress swamp forests, prairies, and freshwater marshes. According to Davis (1943), pine flatwoods once dominated the landscape of the area, but have been significantly reduced by urban and agricultural development. Today, they still represent the "native ecosystem" of greatest extent and are interspersed with freshwater marshes and wet prairies (USACE and SFWMD 2004). Forested wetlands are scattered throughout the study area, but the most significant stands within the study area occur along the banks of the North Fork, the Atlantic Ridge, the V-2 Ranch, Cypress Creek, Trail Ridge North, and Trail Ridge. Remnants of Florida scrub habitat exist along the Atlantic Coastal Ridge (Fernald 1989), along the North Fork of the St. Lucie Estuary, and along the Holopaw-Indiantown Ridge.

4.9.2 Fish and Wildlife Communities

The fish and wildlife populations in the Indian River Lagoon have been strongly influenced by the long-term effects of drainage and development within the watershed. A major goal of the Indian River Lagoon restoration process is to remedy some of the harmful effects caused by the original Central and Southern Florida Flood Control Project that, in hindsight, has been detrimental to animal communities.

Approximately 700 invertebrate species have been identified in the St. Lucie Estuary and Indian River Lagoon (Virstein and Campbell 1987). The American or eastern oyster (*Crassostrea virginica*) is an important species within the St. Lucie Estuary. It occupies sediment-free, firm-bottom substrates under brackish and saltwater conditions. The bars and reefs formed by oysters provide important habitat and attachment areas for numerous organisms including oyster spat, mussels, tunicates, bryozoans, and barnacles (Woodward-Clyde 1998). They have been recognized for their species richness (Pearse and Wharton 1938, Wells 1961, Bahr and Lanier 1981). Oyster communities provide food for fish and crustaceans, provide attachment areas for sessile organisms (i.e., barnacles, sea anemones), provide habitat as nursery areas and refuge from predators, provide spawning substrate for fish (i.e., gobies, blennies), stabilize bottom sediments for other benthic organisms (i.e., hard clams) and aquatic plants, and concentrate prey for larger predator fishes. Oysters are filter feeders and remove suspended algae and other particles from the water columns, thereby improving water clarity and allowing seagrass communities to grow at greater depths within the estuary.

In addition to the invertebrates, Gilmore (1977, 1988) described over 800 species of fish that spend part or all of their life in the estuary. These species include important recreational and commercial species such as spotted seatrout, red drum, snook, tarpon, gray snapper, and sheepshead. Urban basin runoff, development, and nutrient enrichment are among the conditions that have contributed to the decrease in numbers of fish in the Indian River Lagoon and St. Lucie Estuary. Because of the limited amount of vegetation and oysters in the estuary, populations of many of the recreationally important fish species (spotted seatrout, red drum, snook, snappers, and mullet) are significantly less than what would be expected in a healthy estuary.

Several species of amphibians and reptiles are found within the Indian River Lagoon Watershed. Amphibians in the area include the southern toad, squirrel tree frog, and pig frog. Common reptiles include the American alligator, red rat snake, eastern diamondback rattlesnake, water moccasin, diamondback terrapin, gopher tortoise, Cuban anole, green anole, southeastern five-lined skink, indigo snake, and southern black racer (Janicki et al. 1999). Sea turtles also occur on near-shore reefs and within the Indian River Lagoon.

The Indian River Lagoon provides habitat for many bird species, including migratory species that use the Atlantic flyway. The lagoon also provides forage areas for seabirds (gulls, terns, pelicans and others), wading birds, and shore birds. Common birds seen in or near the Indian River Lagoon include double-crested cormorant, anhinga, waders (heron, wood stork, egret and ibis), rail, moorhen, snipe, turkey vulture, black vulture, hawk, American bald eagle, owls, American kestrel, quail, wild turkey, common ground dove, woodpeckers, blue jay, American crow, blue-gray gnatcatcher, northern loggerhead shrike, gray catbird, northern mockingbird, brown thrasher, European starling, ovenbird, northern cardinal, rufous-sided towhee, sparrows, warblers, and common grackle. Loss of seagrass beds and oyster reefs, coupled with the development and drainage of wetlands and conversion to agriculture has decreased the populations of some the previously mentioned bird species.

Common mammals in the watershed include the Virginia opossum, nine-banded armadillo, eastern cottontail rabbit, eastern gray squirrel, raccoon, bobcat, white-tailed deer, Sherman’s fox squirrel, cotton mouse, feral hogs, and feral cats and dogs. Bottlenose dolphins and West Indian manatees are sometimes present in the lagoon.

Fifteen federally listed threatened (T) or endangered (E) animal species and five federally listed plant species are present or potentially present in the project area. Most of these species have been previously affected by habitat degradation due to wetland drainage, excess nutrient runoff, and changes in wetland hydroperiods. These species include West Indian manatee (E), snail kite (E), wood stork (E), red-cockaded woodpecker, (E), Florida scrub-jay (T), Audubon’s crested caracara (T), whooping crane (E), bald eagle (T), eastern indigo snake (T), Florida panther (E), and five species of sea turtles: the Atlantic loggerhead (T), Atlantic green turtle (E), leatherback turtle (E), Atlantic hawksbill turtle (E) and Atlantic ridley turtle (E).

Endangered and threatened plant species include three flowering plant species: tiny polygala (E), four-petal paw paw (E), and fragrant prickly-apple (E). A lichen, Florida perforate cladonia (E), is also found in the area. These four species are commonly found in sand hills, open pine scrub, and rosemary scrub (the lichen). The fifth plant species is the threatened Johnson's seagrass, a benthic plant present in the southern Indian River Lagoon.

For more information regarding the vegetation and animal communities of the project area, see Sections 3.5 and 3.6 of the Indian River Lagoon – South Project Implementation Report (USACE and SFWMD 2004).

Section 5.
Overview of Technical Approach and Description of Tools

5.1 Overall Technical Approach

A resource-based approach was used to develop the water reservation for the North Fork of the St. Lucie River. Technical evaluations included a summary of available empirical data, modeling analyses, and literature references. The approach consisted of the following five basic steps:

1) Identification of key ecological compartments within the St. Lucie River that may benefit from a water reservation. The compartment identified was the North Fork of the St. Lucie River.
2) Identification of fish and wildlife resources or habitat to be protected. The low salinity zone (described in **Section 6**) within the North Fork was identified as critical habitat for larval and juvenile fishes.
3) Identification of the salinity performance measure and flow target for the key ecological compartment. Maintaining a dynamic distribution of the 1 psu isohaline at preferred locations within the North Fork of the St. Lucie River was identified as the performance measure. Pulsed freshwater inflows delivered from Ten Mile Creek (Gordy Road Structure) that equate to a mean monthly flow of 130 cfs was identified as the flow target.
4) Quantification of water made available by the project over a timeframe representative of average, wet, and dry hydrologic conditions. A combination of modeling tools was applied that provided watershed inflows and salinity conditions within the North Fork for the 2050 Future with Project and 2050 Future without Project Conditions over a 41-year simulation period.
5) Quantification of the water to be reserved for the protection of fish and wildlife. This was achieved by plotting the 2050 Future with Project Condition time series as a volume probability curve comparing these values to the flow target and reserving the amount of water needed for the protection of fish and wildlife.

Each step and an overview of the inputs are illustrated in **Figure 5.1**.

5.1.1 Identification of the Key Ecological Compartments

A key objective in the development of a water reservation is selection of an area or compartment of the water body that contains a resource sensitive to low flows. The key ecologic compartment selected for the water reservation is the North Fork of the St. Lucie River. This area contains a low salinity zone that has been documented as critical habitat for many estuarine and marine organisms and is sensitive to low flows. Although the North Fork is not the only ecological compartment identified within the Indian River Lagoon – South Project Implementation Report, the rerouting of additional flows to the North Fork will help to restore a more natural distribution of flows to the St. Lucie Estuary and help to preserve oligohaline habitat, which have been identified as important objectives of the Indian River Lagoon – South Project.

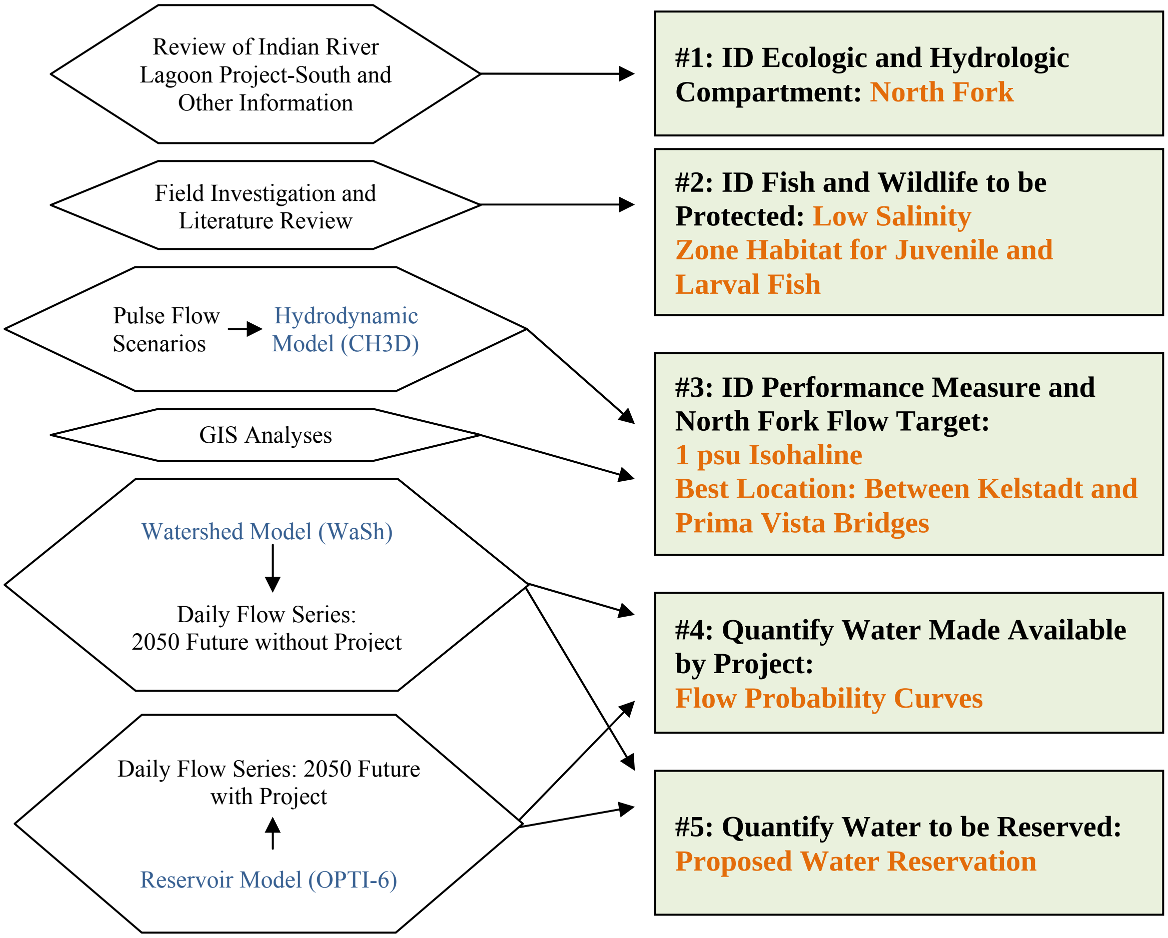

Figure 5.1. Overview of information used to develop the proposed water reservation for the North Fork of the St. Lucie River.

5.1.2 Identification of Fish and Wildlife or Habitat to be Protected

A combination of the valued ecosystem component approach developed by the United States Environmental Protection Agency (USEPA 1987) and the habitat overlap concept (Browder and Moore 1981) were used to focus on critical estuarine habitat needed to protect fish and wildlife within the North Fork of the St. Lucie River. The valued ecosystem component approach assumes that providing environmental conditions that protect the targeted component will also result in protection of the entire community. The habitat overlap concept was used to relate the effects of freshwater discharge on the physical location of the low salinity zone (0–10 psu) and the quality of habitats that serve as nursery grounds for estuarine biota. In this application, freshwater inflows derived from the Ten Mile Creek Basin delivered by the Gordy Road Structure (**Figure 4.1**) produce a temporal and spatial overlap between the location of the low salinity zone and critical riverine habitat that serves as a nursery area for larval and juvenile fishes (**Section 6**). Based on a review of available data and its importance to the ecology of St. Lucie Estuary, the low salinity zone was identified as the valued ecosystem component for the North Fork of the St. Lucie River.

5.1.3 Identification of Performance Measures and Hydrologic Targets

Performance measures and targets generally relate to how well (or poorly) a particular water management alternative may affect the selected valued ecosystem component. The performance measure must relate to conditions within a system that affect fish and wildlife, be quantifiable, be related to a specific target, and indicate when the target has been reached or measure the degree of change toward meeting the target when it has not been reached. The target must represent the desired value of the performance measure.

To measure the effectiveness of the proposed water reservation, a salinity performance measure and flow target were developed for the North Fork of the St. Lucie River. Both the performance measure and hydrologic target relate to the low salinity zone as critical habitat for juvenile and larval fish within the North Fork of the river. The performance measure relates to a salinity value that places an ecologically relevant component of the low salinity zone, the estuarine turbidity maximum, in the desired location within the North Fork (see **Section 6**). Hydrodynamic modeling was performed to define a range of mean monthly flows that could serve as potential flow targets for the North Fork (see **Section 7**). Pulsed flows, as described below, served as the basis for flow scenarios developed using the hydrodynamic model. The pulsed flow scenario that best placed the salinity performance measure at the target location within the North Fork was chosen and converted to a mean monthly flow target.

5.1.3.1 Pulsed Inflows

One of the ways estuaries experience energy transfer is through the pulsing of water. These pulses may take a variety of forms, including watershed runoff or inflow, tides, and floods (Day 2001). Odum (1969) developed relationships between ecosystem state, disturbance level, and energy flow. These relationships are based on successional theory that predicts that ecosystems that are frequently disturbed (such as by a pulse of water) maintain high, but simple energy flows by virtue of the life history characteristics of species able to tolerate such disturbances. Since trophic interactions are the main pathways by which energy moves through an ecosystem (Odum 1984), biological responses naturally result from energy transferred by the pulsed water inflow. Organisms not only adapt to physical disturbances or pulses but models indicate that optimal levels of pulsed physical energy increase gross production (Odum et al. 1995). Fluctuating freshwater inflows (i.e., pulsed inflow) and ocean-driven lunar tides are the primary means by which physical pulsed energy flow occurs in riverine estuaries like the North Fork of the St. Lucie River with freshwater inflow as the predominant source of seasonal and inter-annual variability in estuaries.

From a hydrodynamic perspective, pulsed flows into estuaries create a dynamic interaction of the freshwater inflows and the daily tidal cycle that moves the freshwater/saltwater interface (1 psu isohaline) to different locations. In contrast, a constant inflow rate maintains a nearly stationary isohaline location after equilibrium is reached. Pulsed flows may also increase mixing and reduce salinity stratification. From a biological perspective, the freshwater/saltwater interface region has been established as an important nursery area for early life stages of fish (see **Section 6**) and the importance of pulsed freshwater flow events to this function in estuarine systems is well documented. For example:

- Improved trophic value for early life stages of fish is expected and associated with the movement of the saltwater/freshwater interface (North et al. 2005, North and Houde 2003)
- Trophic value accrues from enhanced secondary production of invertebrates associated with the saltwater/freshwater interface (Diaz and Schaffner 1990)
- Increased turbidity from pulsed inflow may also reduce predation on fish larvae (Kimmerer 2002, North et al. 2005)
- Episodic events may have an important role in controlling fish recruitment (North et al. 2005).

Reports of controlled pulsed releases for the purpose of providing environmental benefits to an estuary are limited. The SFWMD has delivered pulse release flows to the Caloosahatchee Estuary to protect salinity-sensitive grass bed habitat from saltwater intrusion in the upper estuary. Pulse releases have been generated to emulate natural rainfall runoff events that produce a hydrograph that quickly advances fresh water downstream, followed by a slow retreat as described in **Section 7.2**. District staff has observed that pulsed inflows emulating a natural runoff event were more effective for moving the saltwater front downstream than constant level inflows of the same discharge volume. These pulse releases also maintained a dynamic low salinity zone, reducing the occurrence of harmful phytoplankton blooms associated with a constant managed flow regime (Haunert and Doering, pers. comm.). The retreat of the saltwater/freshwater interface up-river following the pulse release has been implicated in enhanced particle (such as eggs) delivery following fish spawning (North et al. 2005). Water managers in California and Texas have also conducted freshwater releases in association with varying environmental objectives (Jassby 2005, Texas Parks and Wildlife 2006, Kimmerer 2002, Palmer et al. 2002).

During the dry season, pulsed inflows of fresh water to the North Fork of the St. Lucie River occur naturally due to intermittent rainfall inputs. Empirical data collected from the St. Lucie River and Estuary shows that an increase in larval and juvenile fish, as well as invertebrate abundance, resulted within the North Fork following a natural pulse release event produced by local rainfall (see **Section 6.6**). The ecological importance of these pulsed inflows and their relationship to the freshwater/saltwater interface (1 psu isohaline), the estuary turbidity maximum, and the life histories of larval and juvenile fishes that utilize the St. Lucie River are summarized in **Section 6**.

5.1.3.2 North Fork Performance Measure and Hydrologic Target Determination

Pulse releases of fresh water to the North Fork of the St. Lucie River were used as the basis to determine the hydrologic target for establishing a water reservation. Different flow scenarios that were based on pulsed releases were developed and evaluated using a hydrodynamic model to determine downstream salinity isohalines. The overall goal of the pulse release is to move the 1 psu isohaline into the desired location between the Prima Vista Bridge and Kelstadt Bridge within the North Fork. GIS analyses presented in **Section 6.5** indicates that the area between these two bridges is the most desired location for the 1 psu isohaline because the quantity of stationary low salinity habitat is increased relative to upstream areas. Empirical data suggests that the 1 psu isohaline corresponds to the location of the ecologically beneficial estuarine turbidity maximum and chlorophyll *a* maximum (described in **Section 6**). This information was used to establish the salinity performance measure (described in **Section 7**).

The slow retreat of the 1 psu isohaline created by pulsed inflows is believed to support maximum re-suspension and trapping of bottom sediments, bacteria, particulate organic matter, and benthic organisms. Increased suspension allows enhanced feeding conditions for fish larvae utilizing this productive habitat (Scully et al. 2002, North et al. 2005). Areas downstream of this location require substantially higher flows to get the same effect because they are much wider. This information was used to develop the flow target associated with moving the 1 psu isohaline to the preferred location along the North Fork of the St. Lucie River.

5.1.4 Quantifying Water Made Available by the Project

One objective of the Indian River Lagoon – South Project was to provide a more natural distribution of flows to the St. Lucie Estuary to benefit fish and wildlife resources. Model application using a 41-year timeframe (1965 through 2005) was an important component for determining the quantity of water made available by the implementation of the Indian River Lagoon – South Project. The time period is representative of average, wet, and dry hydrologic conditions. An integrated modeling framework combining watershed (WaSh), reservoir optimization (OPTI-6), and estuarine hydrodynamic (CH3D) models was applied to determine the volume of water made available by the project. **Section 7** describes the model formulation and application. The results of the watershed and reservoir optimization modeling produced a flow time series representing the 2050 Future without Project Condition and 2050 Future with Project Condition (described in **Sections 5.1.4.1** and **7.3.1**), while the hydrodynamic model was used to develop a flow target for the North Fork of the St. Lucie River (described in **Section 7.2.1**). These results are used in **Sections 8** and **9** to quantify the amount of water to be reserved in the North Fork of the St. Lucie River to protect fish and wildlife. Additional salinity time series were produced from the estuarine hydrodynamic model to develop frequency distribution curves for various isohalines to identify benefits associated with the flow target created for the North Fork.

5.1.4.1 2050 Future With and Without Project Condition Time Series

The St. Lucie Estuary Watershed Model (WaSh) was used to develop flows representing the 2050 Future without Project Condition. The WaSh model domain includes the seven major basins that discharge surface water to the St. Lucie Estuary. Model inputs include 1965 through 2005 rainfall and evapotranspiration estimates, projected 2050 land use, agricultural water demands, and urban water supply demand assumptions.

Results from the WaSh model were incorporated into the Reservoir Operation and Optimization Model (OPTI-6). The OPTI-6 model incorporated the Indian River Lagoon – South Project footprint, which contains the proposed reservoirs, canals, and wetland areas to be restored. From this information, flows for the 2050 Future with Project Condition land use were created for input to the OPTI-6 model (**Section 7.3.1**). The OPTI-6 model was then used to: (1) optimize the amount of water that could be captured, stored and attenuated in the project reservoirs to reduce high volume discharges to the mid-estuary that impact oyster populations, (2) redistribute flows to the North Fork to protect the low salinity zone and its associated fish and wildlife resources, and (3) maintain Central and Southern Florida Flood Control Project levels of service for flood protection and water supply. Results from the OPTI-6 model simulations were used to create the 2050 Future with Project Condition flow time series. These results were generated specifically for development of the water reservation, as described in the analyses in **Section 7.3.1**. All Indian River Lagoon – South Project features are simulated including: (1) reservoir and storage pumps, (2) stormwater treatment area and design release rates, (3) diversions from the C-24 Stormwater Treatment Area to the North Fork, (4) diversions from the C-23 Canal to the C-44 Reservoir/Stormwater Treatment Area, and (5) restored natural lands. However, the flows generated for the 2050 Future with Project Conditions are not fully consistent with the Indian River Lagoon – South Project simulations or other recent evaluations listed in **Section 1**. Specifically, the pumps and structures are operated with different rules than those used in the Indian River Lagoon – South Project simulations. Further, the simulations for this analysis uses an expanded (41-year) and recalibrated WaSh model.

5.1.5 Identification of Water to Be Reserved

The daily flow time series (the 2050 Future with and without Project Conditions) produced by the model applications as described above were converted to mean monthly values and used to construct volume probability curves (see **Section 8**). The 2050 Future with Project Condition was compared against the North Fork flow target, which is also expressed in terms of a mean monthly flow value. The water to be reserved for protection of fish and wildlife was identified as the portion of available water delivered by the 2050 Future with Project Condition up to, but not exceeding, the North Fork target flow (described in **Section 9**). Therefore, during the dry season all 2050 Future with Project flows less than the target (mean monthly flow of 130 cfs) would be reserved for the protection of fish and wildlife.

5.2 Modeling Tools

Modeling tools were used to both define existing hydrologic targets and produce output that could be used to quantify the volume of water needed to protect fish and wildlife. During development of the Indian River Lagoon – South Project Implementation Report (USACE and SFWMD 2004), a suite of models incorporating watershed hydrology, water resources optimization, estuary salinity, and ecologic response in the mid-estuary was applied to develop the preferred alternative. Application of these models is described by Wan et al. (2002) and in **Appendices C** and **D.**

Since the completion of the project implementation report, significant advances have been made in developing and updating these modeling tools. Specifically, the St. Lucie Estuary Watershed (WaSh) Model was developed to simulate the St. Lucie Estuary watershed hydrology and replaces the Hydrologic Simulation Program-Fortran (HSPF) that was used previously in the project implementation report (USACE and SFWMD 2004). As described in **Section 7**, the WaSh model was applied to produce a flow time series to represent the 2050 Future without Project Condition, which simulates the watershed hydrology as if no project components are built. The reservoir optimization model, OPTI-5, was updated with approximate fuzzy (approximate rather than precise) operational rules and an off-line reservoir scheme to better reflect project conditions. The revised model, OPTI-6, was applied in the development of the water reservation to produce a flow time series of optimized flows from the project reservoir and canals that could best meet the proposed flow target at the Gordy Road Structure representing the 2050 Future with Project Condition (described in **Section 7**). In addition, a three-dimensional hydrodynamic/salinity model based on CH3D (Curvilinear-grid Hydrodynamic 3-Dimensional) was developed to simulate the salinity distribution throughout the estuary. It was used both in the determination of the flow target development and to identify benefits of the project. A brief summary of the models and their development is below. Model formulation and application are presented in **Section 7**. More detailed technical documentation for each model is provided in **Appendices C** and **D**.

5.2.1 St. Lucie Estuary Watershed Model

The development of the WaSh model was initiated several years ago with the aim of integrating and improving earlier modeling work conducted by the District using the HSPF model with advanced schemes to simulate the complex canal network and flat terrain of South Florida (Wan et al. 2003). The WaSh model uses the HSPF hydrologic process simulation algorithms to represent surface water hydrology, a two-dimensional groundwater model to represent the surficial aquifer, and a full dynamic channel routing model to simulate structure operation and the canal network flow routing. An irrigation routine in the model allows for simulation of irrigation demand. The fundamental time step for the model is one day and the output is provided in daily increments. However, certain model algorithms operate at shorter time steps (30 minutes to 1 hour) to provide accurate representations of physical processes and ensure numerical stability. The domain of the WaSh model is the entire St. Lucie Watershed. The model utilized cell sizes from 500 feet by 500 feet for the minor basins and 2,000 feet by 2,000 feet for the primary basins. GIS data was used to generate the model grid. The District has used the model for several initiatives, including the C-44 Reservoir Project and the development of the Northern Everglades Estuary Protection Program (SFWMD 2008). In the development of the proposed water reservation, the WaSh model was applied to produce a flow time series to represent the 2050 Future without Project Condition. This time series was used in turn to estimate the quantity of water available in the future (**Sections 8** and **9**). A summary of model formulation and application is in **Section 7** and more detailed information is provided in **Appendix C**.

5.2.2 Reservoir Operation and Optimization Model

The St. Lucie Reservoir Operation and Optimization Model (OPTI) was developed for the Southern Indian River Lagoon Feasibility Study (USACE and SFWMD 2004) to optimize the size and operation of the storage reservoirs and stormwater treatment areas. Version six (OPTI-6), updated for application in this proposed water reservation, incorporates the option of off-line reservoirs along with fuzzy logic to produce operation rules (Wan et al. 2006).

Two fundamental components of OPTI-6 are genetic algorithms and a drainage network simulation model (**Figure 5.2**). The genetic algorithm optimizes water control structure operations, which are then evaluated through the daily drainage network simulation model. The drainage network simulation model replicates water moving through the canal system, among canals, reservoirs and stormwater treatment areas, and from basin to basin. Thus, the daily basin flows and daily irrigation demands obtained from the WaSh model are the needed input data for OPTI-6. The daily simulation results are evaluated for mean monthly frequency distributions of freshwater inflows, water supply reliability, and required storage capacity, which are returned to the genetic algorithm for improvement in the fitness. Details of the theory and application of the OPTI-6 model are further explained in Wan et al. (2006) and **Appendix C**.

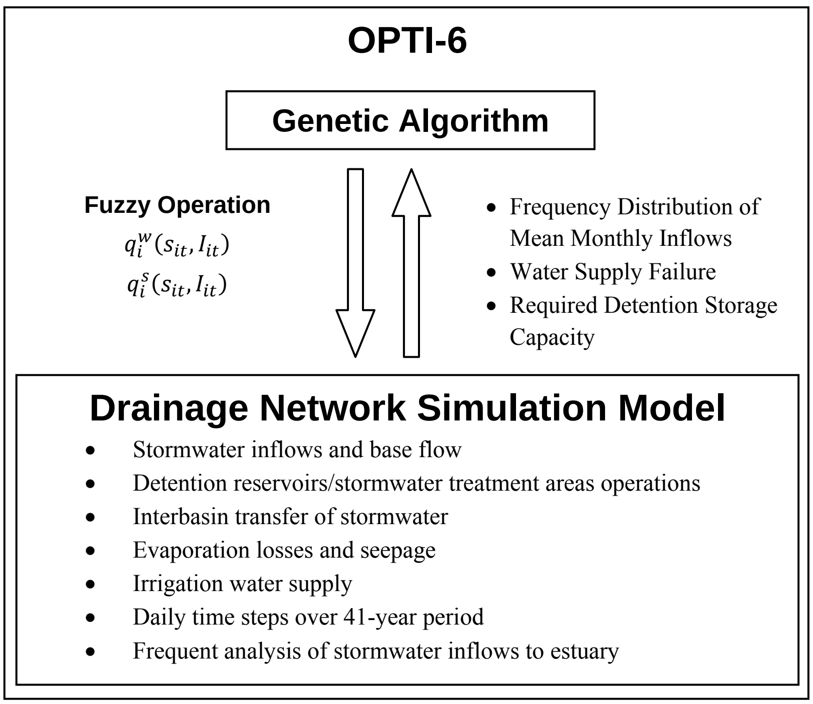

Figure 5.2. Interaction of the genetic algorithm in OPTI6 for optimizing fuzzy operating rules with drainage network simulation model (Wan et al. 2006).

For the Indian River Lagoon – South Project Implementation Report (USACE and SFWMD 2004), the OPTI-6 model was designed to optimize watershed reservoir operations to meet: (1) the target distribution of the total inflow to the mid-estuary consistent with project objectives, (2) irrigation demand, and (3) minimum required reservoir storage capacity. To develop the water reservation, the model's objective function was revised to include a North Fork low salinity zone flow demand, which was not originally considered in the Indian River Lagoon – South Project (USACE and SFWMD 2004). With this revision, optimal size and operating rules were determined for the detention reservoirs in the St. Lucie Watershed to: (1) achieve a specified dry season flow target for the North Fork of the St. Lucie River (mean monthly flow of 130 cfs), (2) supply water from the watershed and reservoirs to satisfy the

Floridan aquifer irrigation demands for a specified reliability, and (3) minimize the required capacities of the detention reservoirs to control project costs. Results from the OPTI-6 model were used to produce a flow time series representing the 2050 Future with Project Conditions. **Appendix C** provides further detail on the development of the OPITI-6 model.

5.2.3 St. Lucie Estuary 3-D Hydrodynamic/Salinity Model

A comprehensive, three-dimensional estuarine hydrodynamic model based on the Curvilinear Hydrodynamics Three-Dimensional (CH3D) code was developed to simulate the hydrodynamics and salinity distribution within the estuarine portion of the St. Lucie River. The CH3D model, originally developed by Sheng (1986), is a non-orthogonal grid model capable of simulating complicated hydrodynamic processes including wind-driven, density-driven, and tidal circulation. The non-orthogonal nature of the model enables it to represent the complex geometry of a meandering water body like the North Fork of the St. Lucie River. Information on the calibration and verification of the model is provided in **Appendix D**.

The model contains a robust turbulence closure model for accurate simulation of stratified flows in estuaries and lakes. The model domain covers the entire estuary from the North Fork to the southern Indian River Lagoon. The CH3D model grid contains 1,168 cells with sizes ranging from less than 30 meters on a side in the North Fork to more than 2,000 meters on a side outside the St. Lucie Inlet within the Atlantic Ocean (**Figure 5.3**). Vertically, four evenly spaced layers enable simulation of vertical stratification within the estuary. The model is driven by external forcing prescribed at the boundaries, including tidal forcing at the ocean boundary, freshwater inflow from controlled structures and runoff from the watershed, and meteorological forcing including wind and rainfall.

As described in **Section 7**, the CH3D model was applied in two different analyses. It was first used to establish the salinity performance measure and flow target for the North Fork of the St. Lucie River. For this application, a series of pulsed release flows were simulated to illustrate the extent and location of the low salinity zone and 1 psu isohaline within the North Fork under a number of flow scenarios. Using these simulations, a target mean monthly flow was established. In separate analyses, the CH3D model was used to produce salinity time series using input flow time series produced from the St. Lucie Estuary WaSh/OPTI-6 models under 2050 Future with and without Project Conditions. The salinity time series were used to construct frequency distribution curves for various isohalines and to identify ecological benefits associated with the flow target created for the North Fork of the St. Lucie River and downstream mid-estuary (see **Section 7.4**).

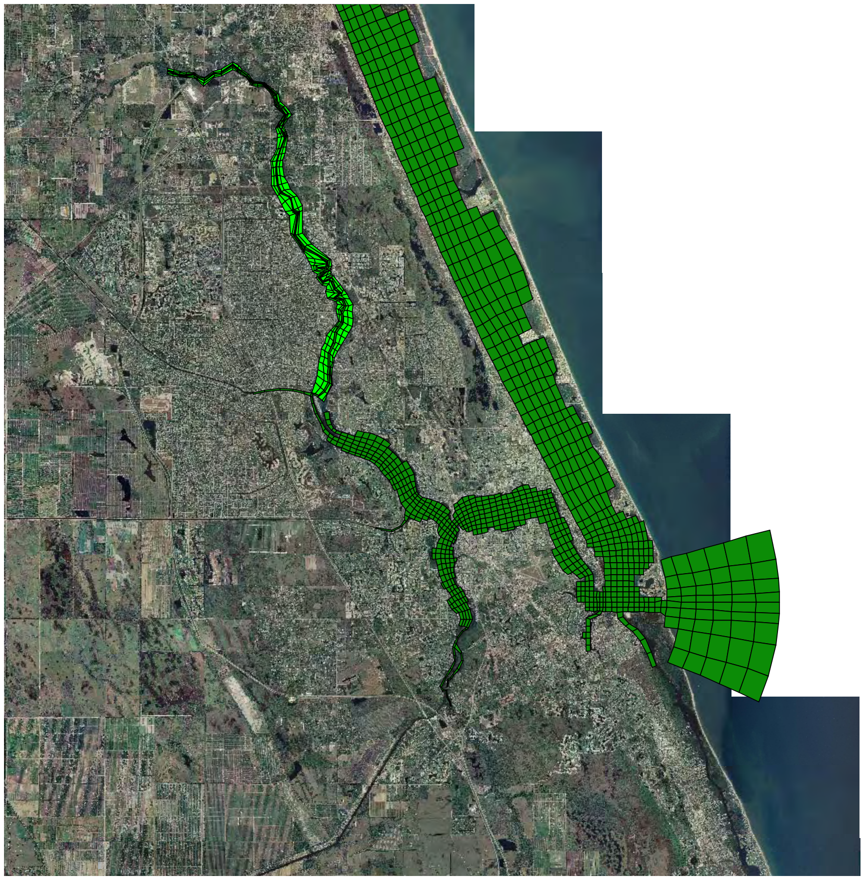

Figure 5.3. The St. Lucie Estuary CH3D model grid.

Section 6. Identification of Fish and Wildlife to Be Protected

This section provides a summary of how District staff identified and selected a valued ecosystem component that is representative of healthy and sustainable fish and wildlife communities within the North Fork of the St. Lucie River. More detailed information on the biological resources present within the river and estuary, including their hydrologic requirements and salinity tolerance levels, may be found in the following source documents:

- Indian River Lagoon – South: Final Integrated Project Implementation Report and Environmental Impact Statement (USACE and SFWMD 2004)
http://www.evergladesplan.org/pm/studies/irl_south_pir.aspx
- Northern Estuaries Performance Measures Salinity Envelopes, CERP System-Wide Performance Measure Documentation Sheet (RECOVER 2007)
http://www.evergladesplan.org/pm/recover/perf_ne.aspx
- St. Lucie River Watershed Protection Plan, Appendix E (SFWMD 2008)
http://www.sfwmd.gov/pls/portal/docs/PAGE/COMMON/PDF/NE_SLRWPP_APPENDICES.PDF
- Technical Document to Support Minimum Flows for the St. Lucie River and Estuary (SFWMD 2002)
http://www.sfwmd.gov/portal/page/portal/pg_grp_sfwmd_watersupply/portlet%20-%20st%20lucie%20river%20and%20estuary/tab1608162/stluciemf-maindoc.pdf

6.1 Approach

The approach used by the District to establish a water reservation for the North Fork of the St. Lucie River is a combination of the valued ecosystem component approach, utilized by the United States Environmental Protection Agency (USEPA 1987) as part of the National Estuary Program, and the habitat overlap concept developed by Browder and Moore (1981). The District has previously used this combined approach to develop a water quality monitoring plan and address minimum flows and levels within the Caloosahatchee River watershed (SFWMD 2003, 2008) and for development of restoration plans for the St. Lucie Estuary (USACE and SFWMD 2004) and Loxahatchee River (SFWMD 2006).

The valued ecosystem component approach has been modified to focus on critical estuarine habitat needed to protect fish and wildlife within the North Fork of the St. Lucie River. In some cases that habitat might be physical, such as an open water low salinity zone. In other cases the habitat might be biological, typified by one or more prominent species (e.g., an oyster bar, mangrove prop roots, grass beds, or floodplain vegetation). Typically these habitats are distributed along an estuarine salinity gradient with different species occupying different portions of the gradient. These habitats are typically critical to the success of many other species that utilize the habitats and the salinity zones in which they occur. This approach assumes that providing environmental conditions that will protect the valued ecosystem component will also protect the entire ecological community.

The overlap concept of Browder and Moore (1981) forms the basis for relating the effects of freshwater discharge on the valued ecosystem component and other estuarine resources. The concept examines the influence of freshwater flow on the quality of habitats that serve as nursery grounds for estuarine biota.

All organisms within an estuary must find areas with acceptable combinations of both salinity and habitat type. Fauna using the estuary are thought to recruit to their preferred salinity (or habitat) zones. Motile animals will move with their preferred salinity zone as it changes position in response to freshwater inflows and tidal influences. The dynamic nature of the overlap of the fixed habitat zone and the constantly moving salinity zone is directly related to the production of commercial or recreational fishery species (Browder and Moore 1981). In the present application, freshwater inflows derived from the Indian River Lagoon – South Project produces a temporal and spatial overlap between the location of the low salinity zone and riverine habitat within the North Fork of the St. Lucie River. The low salinity zone has been well documented in the literature as important nursery habitat for estuarine and marine larval and juvenile fishes. (Odum et al. 1984, North and Houde 2001, 2003, North et al. 2005, Diaz and Schaffner 1990, Yozzo and Diaz 1999, Gilmore 2007).

The District identified the oligohaline zone (representing 0-5 psu) as the valued ecosystem component for the development of minimum flows and levels criteria for the North Fork of the St. Lucie River (SFWMD 2002). At the time of its development, very little empirical data was available and minimum flow and level criteria were based primarily on the presence of adult species and life histories of estuarine and marine fishes present within the river and downstream estuary that may have utilized the oligohaline zone during part of their life cycle. Since that time, several field studies have been completed to provide more information on the processes and organisms that are present in the North Fork (see **Sections 6.5**, **6.6**, and **Appendix E**).

For the North Fork of the St. Lucie River, the following valued ecosystem components were considered:

1) **Shoreline and Floodplain Vegetation –** Past dredging of the North Fork has resulted in berms along the shoreline and a straightened river channel that limits floodplain inundation except during highest flow periods. Following these high flow events, river stages quickly return to levels that restrict flow between the river channel and adjacent floodplain. Because of these physical limitations, the potential for the manipulation of floodplain hydroperiod to restore shallow water aquatic habitat is limited. As a result, shoreline and floodplain vegetation were not selected as the valued ecosystem component of choice for the North Fork of the St. Lucie River

2) **Oysters** – Biological surveys show that oysters are not present within the low salinity waters of the North Fork of the St. Lucie River. Low salinity levels cause oyster stress and mortality. Since oysters do not exist within the North Fork, this community would have made a poor choice as a valued ecosystem component.

3) **Submerged Aquatic Vegetation** – For the past three decades the only submerged aquatic vegetation communities documented in the North Fork of the St. Lucie River and Estuary have been very small, ephemeral patches of tapegrass (*Vallisneria americana*) near the mouths of small freshwater tributaries, and widgeon grass (*Ruppia maritima*) in shallow, sandy shoreline areas of the estuary. Significant populations of submerged vegetation are not present within the North Fork of the St. Lucie River and therefore were not selected as the valued ecosystem component.

4) **Benthic Macroinvertebrates** – Benthic macroinvertebrate species composition and abundance in relation to substrates in estuaries has frequently been used to characterize estuarine health and potential food supply for benthic feeding animals, especially juvenile fishes. Quarterly sampling of macroinvertebrates within the North Fork revealed the highest densities of these organisms occurred in the river rather than in the estuary. These data have been used to support the importance of North Fork river habitat as a food source and nursery habitat for larval and juvenile fishes. However, samples have not been collected frequently enough to develop a relationship between their species composition and abundance, salinity, and river flow at the time scale needed to conduct this evaluation. For these reasons, benthic macroinvertebrates were not selected as the valued ecosystem component of choice for the North Fork of the St. Lucie River.

5) **Larval and Juvenile Fishes** – Providing favorable nursery habitat for larval and juvenile fishes is an important objective for restoration of the North Fork of the St. Lucie River. However, larval and juvenile fish sampling of the North Fork is limited (see **Appendix E**). Prior to this study, relatively little information exists for the St. Lucie River that establishes a relationship between larval and juvenile fish species composition and abundance, salinity, and river flow. For this reason, larval and juvenile fish were not directly selected as the valued ecosystem component for the North Fork of the St. Lucie River.

6) **Low Salinity Zone** – Based on a review of available data and its importance to the estuary, the low salinity zone within the North Fork of the St. Lucie River was identified as the valued ecosystem component of choice based on the following relationships:

    a) The low salinity zone (0-10 psu) located at the head of an estuary represents a highly productive area considered critical to the life histories of many estuarine and marine organisms. These low salinity areas serve as important nursery habitat for larval and juvenile fishes and provide protection from marine predators (Odum et al. 1984, North and Houde 2001, 2003, North et al. 2005, Diaz and Schaffner 1990, Yozzo and Diaz 1999, Gilmore 2007).

    b) Within the low salinity zone, the estuarine turbidity maximum and chlorophyll *a* maximum (**Figure 6.1**) serve as abundant food sources for zooplankton and benthic invertebrates that become prey for larval and juvenile fishes (Schubel 1968, Jassby et al. 1995, Fain et al. 2001, North and Houde 2001, 2003, North et al. 2005).

    c) The low salinity zone also serves as habitat for a broad array of other estuarine species, including many that are recreationally and commercially important (Odum et al. 1984, Jassby et al. 1995, Fain et al. 2001, North and Houde 2001, 2003, North et al. 2005).

    d) Using models and empirical data, hydrologic relationships can be established between surface water inflows and the location of the low salinity zone within the North Fork of the St. Lucie River (**Section 7**).

6.2 Ecological Importance of the Low Salinity Zone

Many species depend on estuaries during some part of their life cycle (Gunter 1961, Day et al. 1989). One of the most salient ecological or resource functions attributed to estuaries is their role as nursery areas for the larval and juvenile stages of many species, including commercially important fish and shellfish (Gunter 1961, Rozas and Hackney 1983, 1984, Odum et al. 1984, Jassby et al. 1995, Fain et al. 2001, North and Houde 2001, 2003, North et al. 2005, Yozzo and Diaz 1999).

The low salinity zone region of an estuary occurs where fresh and saline waters meet with salinities typically ranging from 0 to 10 psu. This area, considered critical to the life histories of many organisms (Holmes et al. 2000, Hughes et al. 2000), provides habitat for a wide variety of adult and juvenile freshwater, estuarine, and marine fishes (Rozas and Hackney 1983, Odum et al. 1984, 1988, Peterson and Ross 1991). Along the east coast of the United Sates, low salinity tidal wetlands provide nursery grounds for many anadromous and catadromous fishes, such as shad, herring (alosids), striped bass (*Morone saxatilis*), and eels (*Anguilla rostrata*) (Massmann 1954). These tidal low salinity areas are the sites of large organic concentrations from river input and in situ production (Odum et al. 1984). Extensive tidal freshwater and low salinity systems are characteristics found in all the major estuarine systems in North America, such as the Columbia River, San Francisco Bay, Hudson River, Delaware Bay, Chesapeake Bay, Pamlico Sound, Albemarle Sound, and the St. Johns and St. Lawrence River estuary systems (Crumbs 1977, Odum et al. 1984, Diaz 1989, Diaz and Schaffner 1990, Jones et al. 1990, Weisberg et al. 1997, Kimmerer 2002). Similarly, extensive tidal freshwater and low salinity systems have been identified in major European systems such as the Baltic Sea and Ele River (Leppakoski 1975, Wolff 1972, Pfannkuche et al. 1975, Pfannkuche 1980, 1981).

Two reasons that so many fish species spend part of their lives in the low salinity zone are the abundance of food sources and protection that is offered. A broad array of micro- and macroinvertebrates live in these areas and serve as an important food source for fish (Diaz and Schaffner 1990, Yozzo and Diaz 1999). Protection from marine predators is also provided in the low salinity zone due to both low salinities and low visibility associated with suspended solids, color, and abundant phytoplankton (Chesney 1989, Kimmerer 2002). This protection may help explain why the smallest fish are typically found in the low salinity zone (Gunter 1961). Thus the low salinity zone is a unique habitat that can offer both protection from predation and an abundant food source for small or larval fishes (Roman et al. 2001, North and Houde 2001, 2003, North et al. 2005).

Marine fish that adhere to a well-documented pattern of adult migration and spawning in marine waters, larval movement inshore, and juvenile residence in estuaries are considered estuarine-dependent species (Gunter 1961, Ross and Epperly 1985). The spawning of a particular species in nearby marine waters usually indicates the presence of fish larvae in low salinity areas of an estuary. Fishes that have been documented to spawn in high salinity waters near the St. Lucie Inlet include sand trout (*Cynosion arenarius*), seatrout (*Cynosion nebulosus*), white mouth croaker (*Micropogonias furnieri*), silver perch (*Bairdella chyrsura*), common snook (*Centropomus undecimalis*), and the fat snook (*Centropomus parallelus*) (Gilmore 2007).

Fisheries data collected from the North Fork of the St. Lucie River (Haunert and Startzman 1980, Gilmore 2007) was used to construct a table of fish species that commonly utilize the low salinity zone during their early life history (**Table 6.1**). These data were used to provide an understanding of how proposed freshwater pulse inflows could help to improve the estuarine nursery function of the North Fork of the St. Lucie River (see **Sections 5.1.3.1** and **7.2**).

Table 6.1. Fish that utilize the St. Lucie Estuary low salinity zone during their early life history that may benefit from additional freshwater pulse inflows, by month from October to June. (**E = eggs, L = larvae, J = juvenile)**.

Common Name *(Scientific Name)*	**Oct.**	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**
Common snook *(Centropomus undecimalis)*	**J**	**J**	**J**	**J**	**J**	**J**	**J**	**J**	**J**
Fat snook *(Centropomus pectinatus)*	**J**	**J**	**J**	**J**	**J**	**J**	**J**		
Redfish *(Scienops ocellatus)*		**J**	**J**	**J**	**J**	**J**			
Sand seatrout *(Cynoscion arenarius)*	**L, J**							**L, J**	**L, J**
Spotted seatrout *(Cynoscion nebulosus)*								**L, J**	**L, J**
Silver Perch *(Bairdiella chrysoura)*								**L, J**	**L, J**
White mouth croaker *(Micropogonias furnieri)*		**J**	**J**	**J**	**J**	**J**	**J**	**J**	**J**
Drum family eggs (Sciaenidae)								**E**	**E**
Striped Mullet *(Mugil cephalus)*					**J**	**J**	**J**		
Ladyfish *(Elops saurus)*	**J**	**J**	**J**	**J**	**J**			**L, J**	**L, J**
Sand perch *(Gerrida)*	**J**	**J**	**J**	**J**	**J**	**J**	**J**	**J**	**J**
Bay anchovy *(Anchoa mitchilli)*	**E, L, J**	**E, L, J**	**E, L, J**	**E, L, J**	**E, L, J**	**E, L, J**	**E, L, J**	**E, L, J**	**L, J**
Herring *(Brevootia tyrannus, B. smithi)*				**J**	**J**	**J**	**J**	**J**	**J**
Hogchoker *(Trinectes maculate)*									**L, J**
Naked goby *(Gobionellus bosc)*	**L, J**							**L, J**	**L, J**
Opossum pipefish *(Microphis brachyurus lineatus)*			**J**	**J**	**J**	**J**	**J**	**J**	**J**

Sources: Haunert and Startzman 1980, Gilmore 2007.

6.3 Low Salinity Zone Processes and Mechanics

Due to inflow variability, the area and location of the low salinity zone varies seasonally in response to rainfall events and can undergo rapid change affecting physical, chemical, and biological variables. These changes also impact the dynamic habitats or sub-areas that exist within the low salinity zone as illustrated in **Figure 6.1**. Material entering the marine environment first undergoes geochemical processes associated with a turbidity maximum within the low salinity zone and then biological processes associated with a productivity maximum (Church 1986). Suspended sediments derived from terrestrial runoff can be trapped in high concentrations near the freshwater/saltwater interface (Jassby 1995, Eyre 1998, Lin and Kuo 2003, North and Houde 2001, 2003, North et al. 2005, Fain et al. 2001). An estuarine turbidity maximum develops due to flocculation and trapping of sediments at this interface. Such zones of high turbidity characterize the upper reaches of partially mixed estuaries around the world (Schubel and Pritchard 1986). These relationships are conceptually illustrated in **Figure 6.1** (see also Eyre 1998, Wolanski et al. 2004).

At the same time, nutrients and other compounds bound to sediments may be released resulting in high aquatic productivity. Because the turbidity maximum suppresses primary production (due to light extinction), a productivity maximum typically develops further downstream in clearer waters (Fisher et al. 1988). The productivity maximum may be composed of several sub-areas including the chlorophyll *a* maximum, followed by zones of high abundance of zooplankton, copepods, and fish larvae (**Figure 6.1**). These zones develop as the algae produced in the chlorophyll *a* maximum are used as a food source by epibenthic feeders such as polycheates, mysids, and amphipods (Diaz and Schaffner 1990). These epibenthic feeders serve in turn as food sources for larval and juvenile fishes. It is generally agreed that freshwater inputs containing nutrients help maintain this production (Fisher et al. 1988, Day et al. 1989, Montagna and Kalke 1992) with higher freshwater flows leading to higher yields of desirable species (Loneragan and Bun 1999).

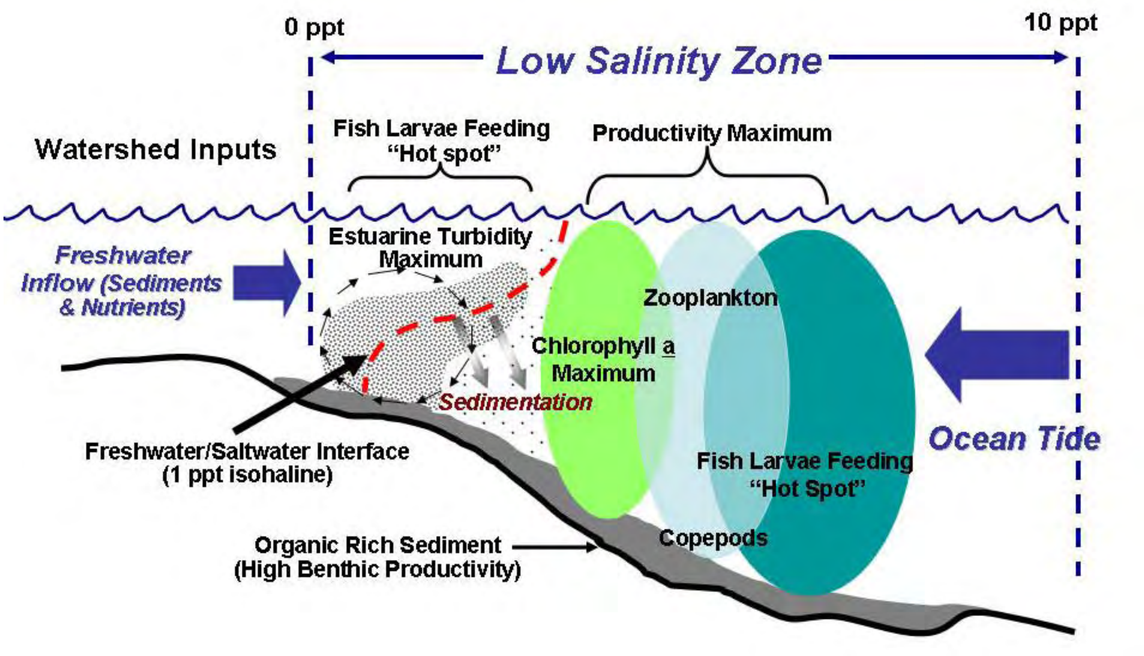

Figure 6.1. Conceptual representation of the low salinity zone and its associated components within a partially mixed estuary (adapted from Eyre 1998).

6.4 Low Salinity Zone Applications within Other Estuaries

Many estuarine fauna are affected by inflow and salinity. Therefore, establishing direct relationships, such as tolerance of individual species to salinity, is most often used to establish inflow management recommendations. However, because modifications of hydrologic regimes in rivers are known to directly and indirectly alter the composition, structure, or function of aquatic ecosystems, scientists tend to agree that it is better to approximate natural flow regimes and maintain entire assemblages of species, than to optimize water regimes for one or a few species (Poff et al. 1997, Richter et al. 1997, Estevez 2000). Although less common, examples of applications using more complex assessments involving trophic relationships (i.e., primary and secondary production) in areas associated with the low salinity zone have been used to develop inflow management guidelines. In particular, an association of fish larvae and secondary production has been tied to zones that equate to the 1 psu to 2 psu isohaline as discussed below. In most cases, these living resources improve in proportion to inflow; however, specific threshold salinities for individual species have not been established.

Spatial and temporal patterns of secondary production in an estuary were demonstrated by Jassby et al. (1995) in a study of striped bass production in San Francisco Bay. An index of freshwater flow was developed using the position downstream from the 2 psu isohaline. This location showed significant relationships with annual measures of many estuarine resources that comprise the food web, including the supply of phytoplankton-derived detritus (particulate organic carbon), benthic macroinvertebrates (mollusks), and crustaceans, smelt, flounder and juvenile and adult striped bass.

For example, the estuarine turbidity zone has been shown to be an important nursery area for larval fishes in the St. Lawrence River Estuary (Dodson et al. 1989, Sirois and Dodson 2000). High concentrations of zooplankton and larval fishes were associated with the leading edge of the estuarine turbidity maximum, which was correlated to salinities of less than 2 psu (Laprise and Dodson 1990). Fish eggs and larvae within these high turbidity areas are typically associated with a zone of increased chlorophyll *a* and zooplankton biomass that serves as an abundant food source for larval and juvenile fishes. Research in the Chesapeake Bay shows that the low salinity zone and associated estuarine turbidity maximum represents critical nursery habitat for striped bass (*Morone saxatilis*) and white perch (*M. americana*). Seasonal changes in river flow pulse events were found to control striped bass and white perch larval survival and recruitment by modifying the physical and biological characteristics of the saltwater front and associated estuarine turbidity maximum (North and Houde 2003, North et al. 2005). Wagner (1999) reported a peak in the rate of littoral fish species turnover that was associated with the tidal freshwater interface (0 psu to 2 psu isohaline) within the tributaries of the Chesapeake Bay. In the San Francisco Bay/Delta, annual measures of larval striped bass survival and abundance were found to be significantly related to changes in the location of the estuarine turbidity maximum in response to freshwater flow (Jassby et al. 1995).

Other studies have indicated the importance of the low salinity zone in terms of secondary production more indirectly. On the west coast of Florida, silver perch, bay anchovy, and other juvenile fish forage within the low salinity zone where organic deposits near the turbidity maximum accumulate. The increased bacterial activity resulting from the foraging by juvenile fish stimulates production of food sources for mysid shrimp and amphipods (Peebles 1996).

In terms of seasonality, studies conducted in southwest Florida showed that the potential for a strong influx of larval and juvenile fishes into low salinity areas was generally highest during the late dry season and early wet season (March to June). The seasonal pattern of larval abundance for southwestern Florida extends from March to October, peaking between April and July (Flannery et al. 2002).

Studies conducted in the Loxahatchee River Estuary (southeast Florida) showed that during the dry season, when freshwater flows are minimal, there is a major influx of tropical fish larvae (Gilbert and Kelso 1971, Nordlie 1979, SFWMD 2006). Many of these species utilize the low salinity zone as critical larval nursery habitat. When larvae develop into juveniles, many seek shallow waters and vegetated shorelines for protection from predation and an abundant food supply. The Restoration Plan for the Northwest Fork of the Loxahatchee River (SFWMD 2006) recommends a dry season flow that would allow an overlapping of essential larvae and juvenile fish habitats within a preferred salinity range of 2 psu to 8 psu.

6.5 Spatial Extent of Low Salinity Habitat within the North Fork of the St. Lucie River

A GIS methodology was used to quantify the location and extent of potential low salinity habitat that currently exists along the North Fork of the St. Lucie River. Using 2004/2005 USGS Digital Ortho Quarter Quad aerial maps, the area of open water, floodplain wetlands, and the length of the shoreline were digitized. From these data, the river was divided into segments in terms of river mile beginning at river mile 0, where the St. Lucie Inlet meets the Atlantic Ocean, extending through the mid-estuary, up the North Fork, and terminating at the Gordy Road Structure (river mile 32.3). The next step was to merge four existing bathymetric data sets of the river and estuary into one file and convert all depths to NGVD 29. Once the shoreline was segmented and the bathymetry data was created, calculations for shoreline length, area, and volume were conducted for the North Fork of the St. Lucie River.

Results (**Figures 6.2** and **6.3**) show the river divided into three relatively homogeneous zones. Zone A (river miles 23 to 32) is the upstream portion of the river characterized by a narrow and discontinuous floodplain. Zone B (river miles 17 to 23) is the central portion of the river, which is dominated by a wider, more continuous floodplain. Zone C (river miles 14 to 17) is the downstream portion where the river widens into an open bay. It is unlikely that Zone C could support a stable low salinity zone due to its size and the volume of fresh water that would be required to be delivered from the upstream watershed during the dry season (see **Figure 6.3**).

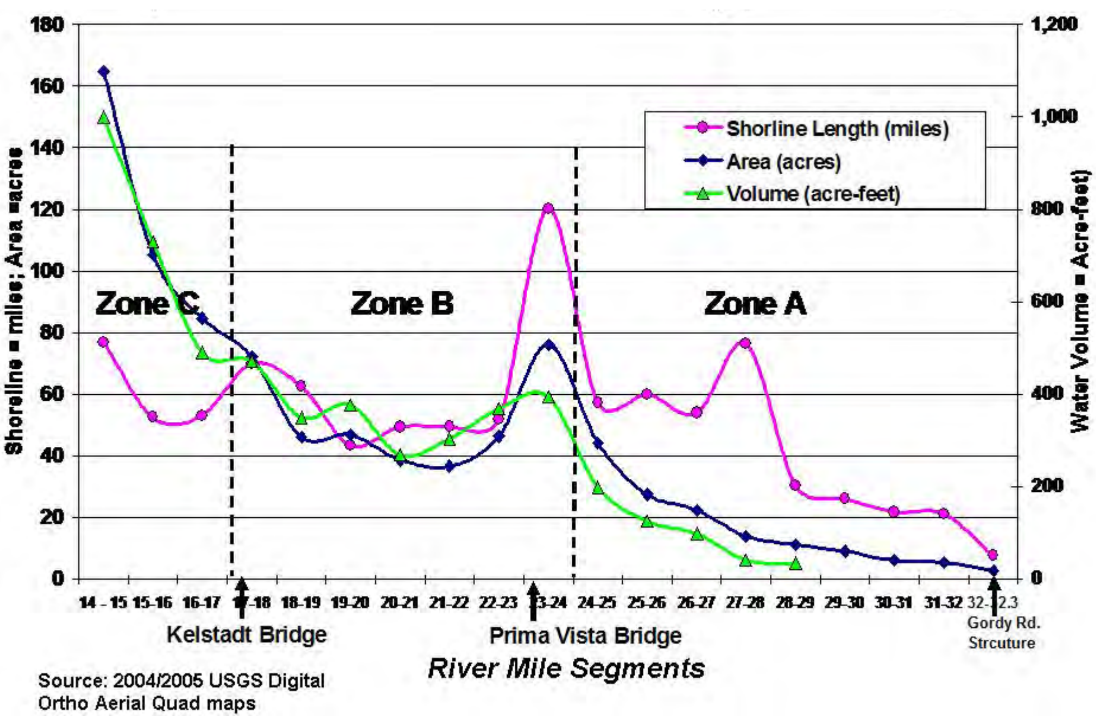

Figure 6.2. Calculations of shoreline length, area, and volume for the North Fork of the St. Lucie River based on GIS analysis of 2004/2005 USGS Digital Ortho Quad Maps and bathymetric data.

Data were compiled on shoreline length, area, and water volume for Zones A through C (**Table 6.2**). Results showed that Zone B provides a 2.5 and 5.1 fold increase in habitat area and volume, respectively, compared to Zone A. In terms of habitat quantity, the amount of open water area and vegetated shoreline (e.g., red mangroves) that can provide low salinity habitat significantly increases within Zone B, as shown in **Figure 6.2** and **Table 6.2**. In addition, the morphology of this portion of the river contains numerous finger canals, oxbows, and meandering river channels that provide preferred low salinity habitat for larval and juvenile fishes. For these reasons, District staff selected Zone B as the focus area for quantifying the volume of water needed to move the low salinity zone to an area of the North Fork of the St. Lucie River that would most benefit fish and wildlife, in this case larval and juvenile fish.

Table 6.2. Calculations of shoreline length, area, and water volume for Zones A, B, and C located along the North Fork of the St. Lucie River.

North Fork Segment	River Miles	Zone	Shoreline Length (miles)	Area (acres)	Volume (acre-feet)
Upstream (Gordy Rd. – Prima Vista Bridge)	RM 32-22	**A**	35.4	142.4	497.5
Midstream (Prima Vista – Kelstadt Bridges)	RM 21-17	**B**	44.7	362.9 (2.5 X larger than Zone A)	2,532.4 (5.1 X larger than Zone A)
Downstream (North Fork Estuary)	RM 17-14	**C**	18.3	354.8	2,219.4

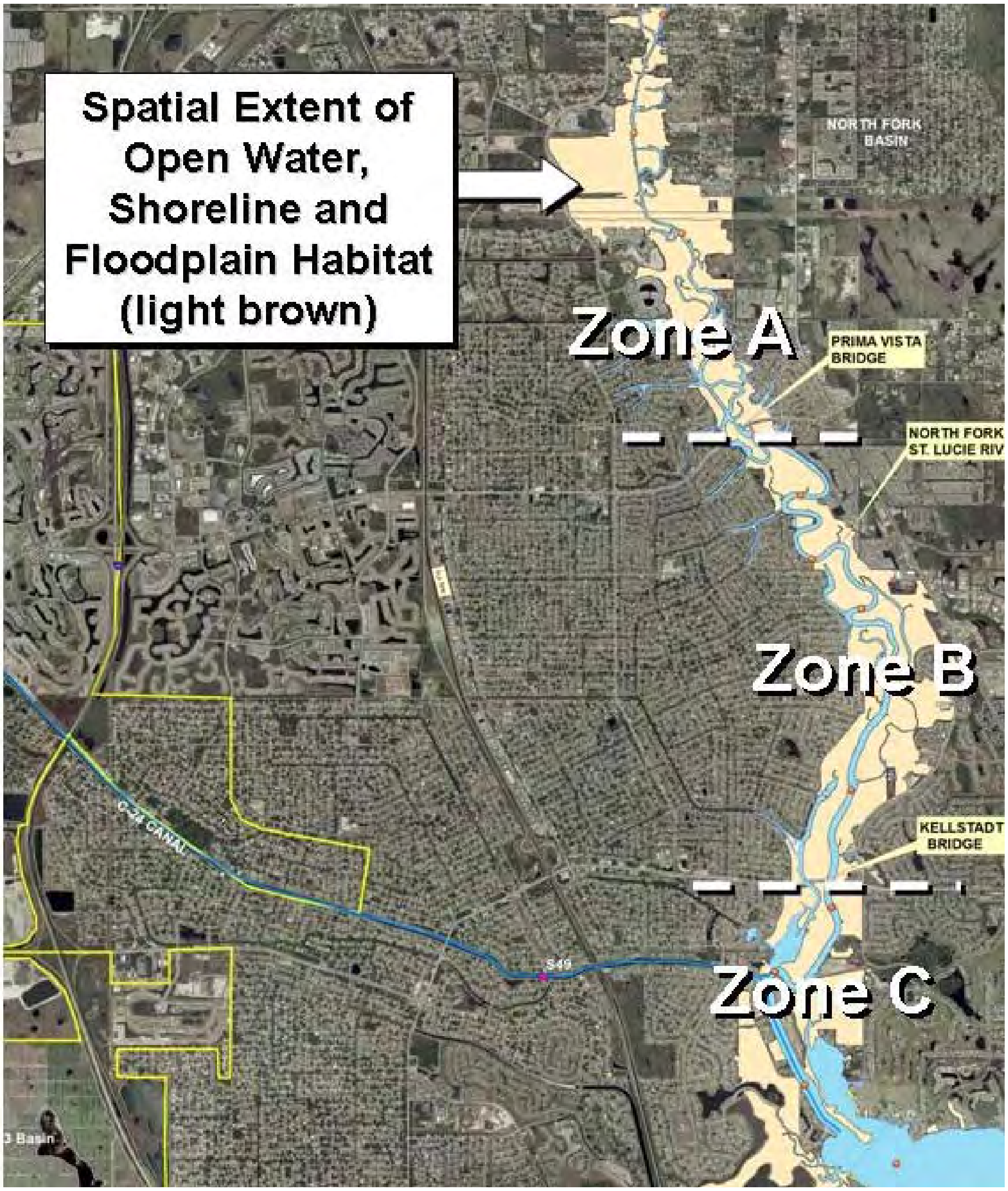

Figure 6.3. Spatial extent of open water, shoreline, and floodplain areas that could serve as potential low salinity habitat shown in relationship to Zones A, B, and C, North Fork of the St. Lucie River.

6.6 Relevant Research Conducted within the North Fork

6.6.1 Estuarine Turbidity Maxima

Fugate and Andreson (2008) demonstrated that an estuarine turbidity maximum frequently exists in this partially mixed system near the freshwater/saltwater interface within the North Fork of the St. Lucie River. This study sampled water throughout the North and South Forks on four occasions during 2008, coinciding with high flow (wet season) and low flow (dry season) discharge conditions during spring and neap tides. Vertical profiles of salinity, temperature, pH, dissolved oxygen, particle size, and total suspended solids were determined in the field while suspended solids (organic and inorganic), chlorophyll *a*, and phaeophytin were ascertained in the laboratory. Observations revealed an estuarine turbidity maximum typically develops at the freshwater/saltwater interface (near the 1 psu isohaline) resulting from the convergence of bottom currents. **Figure 6.4** presents results from this study for a transect taken from the lower portion of the river.

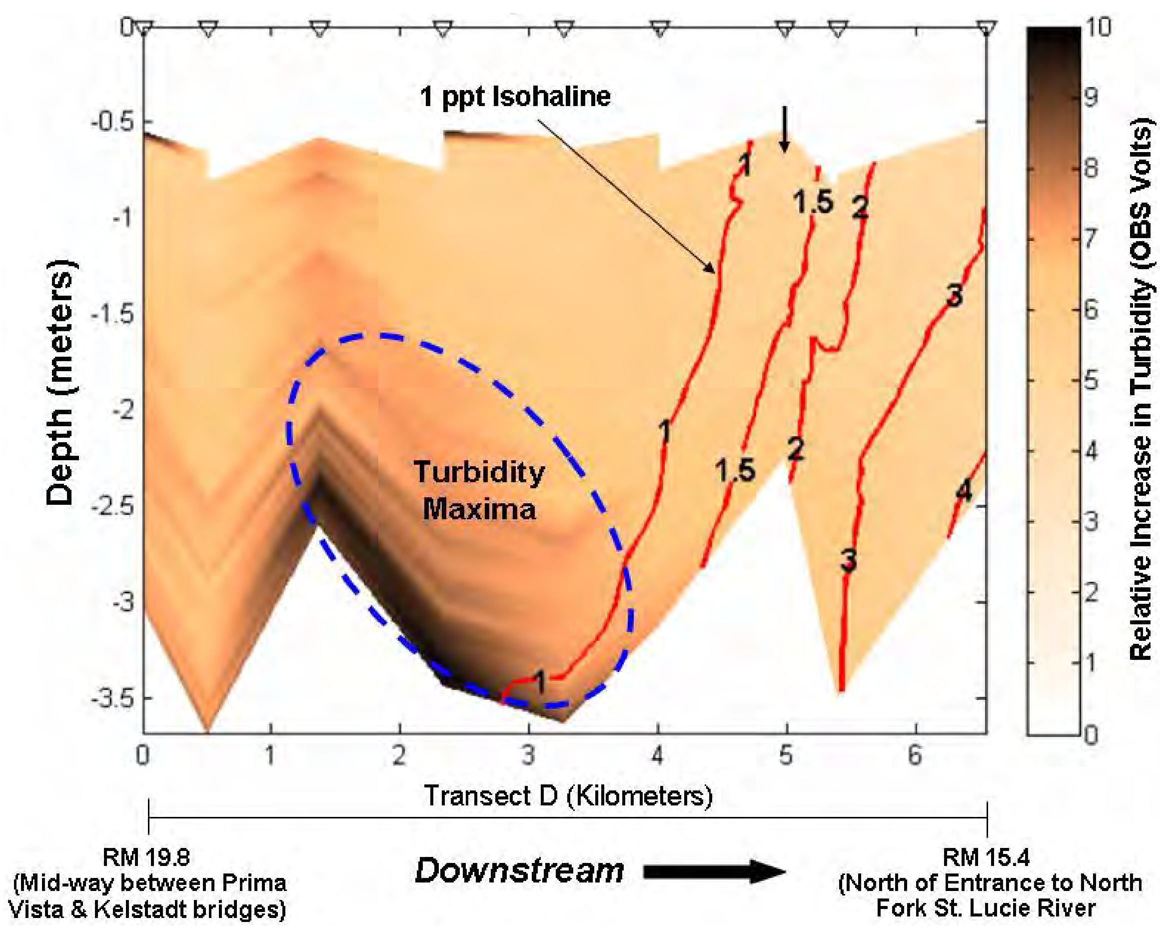

Figure 6.4. Example of the relationship between the estuarine turbidity maximum and the location of the 1 psu isohaline within the North Fork of the St. Lucie River on April 3, 2008 (Fugate and Andreson 2008).

Results demonstrate the relationship between the presence of the estuarine turbidity maximum and the location of the 1 psu isohaline within the North Fork of the St. Lucie River during the dry season. Results also suggest that the size of the particles within the estuarine turbidity maximum were larger, presumably due to changing electrostatic forces that induce flocculation of suspended sediments in this area.

The estuarine turbidity maximum is typically located upstream within the North Fork during low flow conditions and moves downstream in response to increasing inflows, typical of a partially mixed estuary. However, when flows from the Ten Mile Creek Basin (Gordy Road Structure) become large enough to position the estuarine turbidity maximum near the confluence of the river and the downstream estuary, the system becomes highly stratified and performs more like a saltwater wedge estuary.

6.6.2 Chlorophyll *a* Maxima

Based on the conceptual model of the low salinity zone presented in **Figure 6.1**, a chlorophyll *a* maximum is also generally associated with the presence of an estuarine turbidity maximum within a partially mixed estuary like the North Fork of the St. Lucie River. The conceptual model shows that high concentrations of phytoplankton (measured as chlorophyll *a*) generally occur immediately downstream from the turbidity maximum (Fisher et al. 1988, Eyre 1998). Field data collected from the North Fork of the St. Lucie River shows that the estuarine turbidity maximum is typically near the freshwater/saltwater interface represented by the 1 psu isohaline (**Figure 6.4**). However, the chlorophyll *a* maximum generally forms a short distance downstream and at salinities generally greater than 1 psu. To determine if this phenomenon is also present within the North Fork of the St. Lucie River, monthly dry season chlorophyll *a* data collected from the Kelstadt and Prima Vista bridges were plotted against salinity concentrations present at the time of sampling (**Figure 6.5**). Results showed that highest chlorophyll *a* levels generally occur within the salinity range of about 0.7 to 3 psu downstream within the North Fork of the St. Lucie River as represented in **Figure 6.5** and the conceptual model.

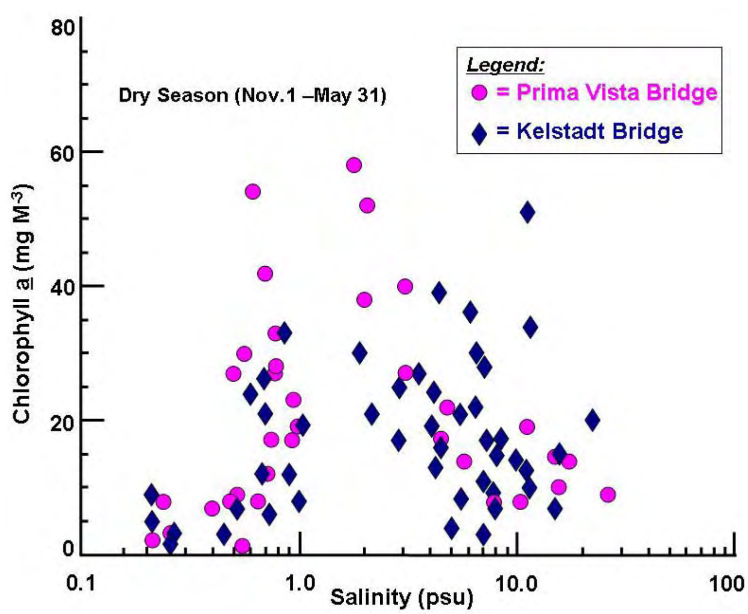

Figure 6.5. Relationship between salinity and chlorophyll *a* levels at the Prima Vista Bridge and Kelstadt Bridge water quality sampling stations, North Fork, St. Lucie River. Data presented represents dry season (Nov. 1 – May 31) values collected from 2003 to 2007 (SFWMD Water Quality Monitoring Program).

6.6.3 Zooplankton Communities

Zooplankton samples were collected from the North Fork of the St. Lucie River and downstream St. Lucie Estuary from May through August 2007. Samples were collected at four locations: (1) Hell's Gate, (2) HR1, (3) Kelstadt Bridge, and (4) Prima Vista Bridge (**Figure 6.6**). These trips were conducted on May 31, June 14, July 16, July 31, and August 14. The samples were collected from the surface and bottom using 500-micron plankton nets. Sample collection began immediately after sunset at mid-flood tide using two boats sampling simultaneously. Approximately 750,000 zooplankton specimens were sorted and enumerated as shown in **Appendix G**. Water quality measurements associated with the sampling were made using an in situ multi-parameter meter that recorded salinity, dissolved oxygen, and temperature data at each sampling site (SFWMD 2009).

The highest number of zooplankton (yellow and blue lines in **Figure 6.7**) generally occurred at the Kelstadt Bridge sampling location, while the lowest abundance occurred near the mouth of the St. Lucie Estuary at the Hell's Gate site (high salinity conditions) and at the Prima Vista Bridge location (freshwater conditions). The zooplankton abundance at Kelstadt Bridge was an order of magnitude higher than the other three sites and the site itself was characterized by low salinity conditions (mean salinity of about 1 psu).

Figure 6.6. Location of zooplankton, benthic macroinvertebrate, and fish larvae sampling stations located within the St. Lucie Estuary and North Fork of the St. Lucie River.

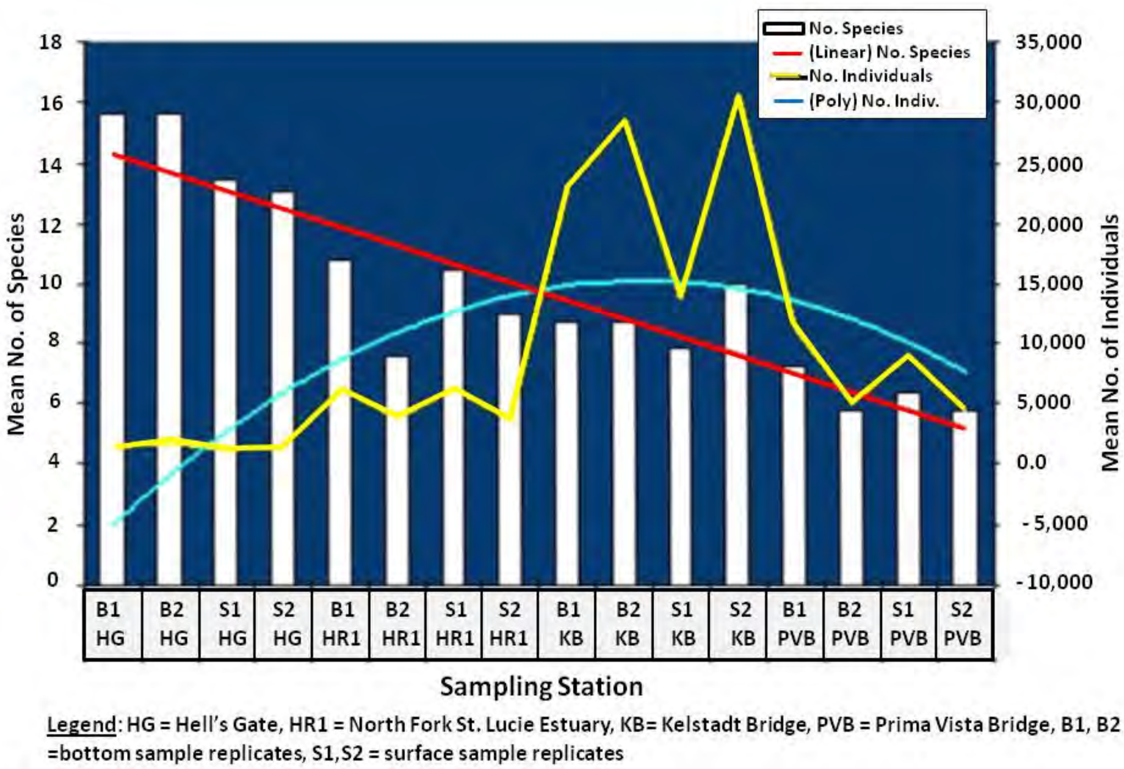

Figure 6.7. Spatial distribution of mean number of species and mean number of individuals captured at each site (May – August 2007). The trend line for mean number of individuals is a polynomial, whereas the trend line for mean number of species is linear (SFWMD 2009).

In terms of species richness, the total number of species present increased with salinity. The lowest values occurred at the Prima Vista Bridge (North Fork of St. Lucie River) in association with freshwater conditions, while highest values occurred at Hell's Gate location (mouth of the St. Lucie Estuary) where highest salinity levels were recorded. The trend exhibited in **Figure 6.7** is a general linear decline in species richness moving upstream from the saltwater-dominated Hell's Gate location to the freshwater Prima Vista Bridge site. High species richness appeared to be associated with high freshwater discharges entering the estuary and reduced salinity levels that coincided with large numbers of freshwater species (e.g., cladocerans, cyclopoid copepods, mysids, and hydrobiid snails) entering the system from upstream locations to mix with more marine and polyhaline species found near the mouth of the St. Lucie Estuary. Highest species richness occurred on August 14, 2007, with over 50 species identified (**Appendix G**). High species richness was associated with the appearance of a saltwater amphipod (*Apocorophium lacustre*) and larval forms of crabs (*Uca* spp.) and midges (*Chaoborus* spp.) collected in August. These data reflect the impact that freshwater inputs have on salinity and zooplankton species diversity and abundance within the St. Lucie Estuary.

Reorganizing the zooplankton data (**Appendix G**) into 10 major groups based on their phylogenetic (evolutionary) development allowed another way to interpret spatial and temporal trends. These 10 groups were further divided into two sets: holoplankton, which spend their entire lives as plankton, and meroplankton, which only spend parts of their life cycles as plankton. The holoplankton identified from the samples included chaetognaths, copepods, cladocerans, and mysids. The meroplankton collected were hydrobiid snails, amphipods, decapod shrimp, porcelain crabs, xanthid crabs, and insects.

Table 6.3 shows three zooplankton groups (amphipods, decapods [shrimp, porcelain crabs and xanthid crabs], and chaetognaths) were most abundant during the spring-dry season (May 31 and June 14, 2007) and declined through the summer-wet season (July 16, July 31, and August 14, 2007). In contrast, on August 14, 2007 (late summer-wet season), large increases in cladoceran, cyclopoid copepod, mysid, and hydrobiid snail zooplankton were observed.

Results showed major changes in the dominant zooplankton groups between sampling periods. These data indicate that zooplankton species composition and abundance can be highly variable within the St. Lucie Estuary and that substantial changes in organism abundance can occur within a two-week period.

Figure 6.8 shows the zooplankton data presented in **Table 6.3** reorganized even further into simply "Red" and "Blue" groups contrasting their relative abundance from May through August 2007. The Red group (amphipods, decapods, and chaetognaths) was most abundant during May and June, while the Blue group (cladocerans, cyclopoid copepods, mysids, and hydrobiid snails) became most abundant in August 2007. In general, the Red group represents zooplankton species found at salinities greater than 15 psu while the Blue group represents zooplankton more often associated with salinities less than 15 psu.

Table 6.3. Comparison of zooplankton prevalence between dry season-spring and wet season-summer sampling trips.

Invertebrate Group	Late Dry Season	Early Wet Season	Wet Season	Wet Season	Wet Season
Spring-Dry Season (Red Group)[1]	***MAY 31***	***JUNE 14***	***JULY 16***	***JULY 31***	***AUG 14***
CHAETOGNATHS	884	664	50	20	16
AMPHIPODS	25,028	34,200	9,000	6,046	2,938
DECA.SHRIMP	2,180	2,545	1,570	96	338
PORCELAIN CRABS	4,220	49,228	132	20	45
XANTHID CRABS	3,954	47,412	15,480	1,138	1,180
TOTALS	**36,266**	**134,049**	**26,232**	**7,320**	**4,517**
Summer-Wet Season (Blue Group)[1]	***MAY 31***	***JUNE 14***	***JULY 16***	***JULY 31***	***AUG 14***
HYDROBIID SNAILS					18,416
CYCLOPOID COPEPODS					45,415
CALANOID COPEPODS	390	4,015	1,754	3,678	2,114
CLADOCERANS					292,928
MYSIDS	927	556	3,934	80,819	22,945
INSECTS		32	104	176	2,170
TOTALS	**1,317**	**4,603**	**5,792**	**84,673**	**383,988**

1 = Blue and Red designations refer to zooplankton groups shown in **Figure 6.8**.
Source: SFWMD 2009

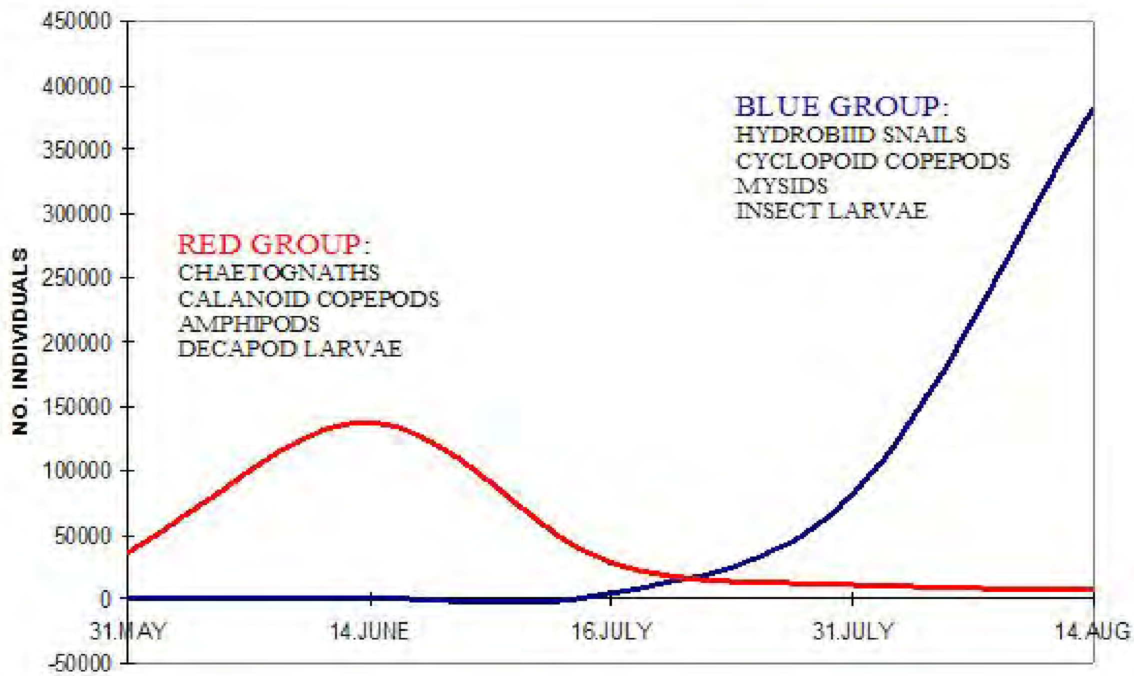

Figure 6.8. Temporal trends in relative abundance for “Red” and “Blue” zooplankton groups for the spring-dry season and summer-wet season (SFWMD 2009).

In summary:

- High zooplankton species richness and low abundance occurred in high salinity areas, while the low salinity areas supported high zooplankton abundance and low species richness.
- Low salinity areas, such as the Kelstadt Bridge, represents the area of highest zooplankton abundance, especially when freshwater inflows reduced salinities to near 1 psu. When this occurs, many of the dominant zooplankton are of freshwater origin.
- Results showed significant differences in zooplankton species compositions for the spring-dry season (high salinity) and summer-wet season (low salinity). When salinities are reduced below about 15 psu, there is a general shift to the summer-wet season zooplankton species composition.
- Sampling at two- week intervals may not be frequent enough to document the high variability of zooplankton species composition or abundances in relation to salinity fluctuations

6.6.4 Benthic Macrobenthos Communities

As part of the CERP RECOVER program, benthic macroinvertebrate communities were monitored at the three stations (Prima Vista Bridge, Kelstadt Bridge, and HR1) within the North Fork of the St. Lucie River and Estuary (**Figure 6.6**). Samples were collected from 2005 to 2007 during November, January, and April (dry season). Monitoring results (**Table 6.4**) showed that regardless of the location of the freshwater/saltwater interface (1 psu isohaline), the density of these macroinvertebrate communities were three to five times greater in the North Fork of the St. Lucie River between the Prima Vista and Kelstadt Bridges than in the center of the North Fork of the estuary (HR1), where the organic content of the sediment was about six times greater (2.7% vs. 18.7%). Species composition data revealed two distinct benthic community assemblages were present, depending on prevailing salinities conditions. When the benthos were exposed to near freshwater conditions for an undetermined amount of time, a bloom of midge larvae (Chironomids) and oligochaete worms dominated the benthic substrate. These organisms were most commonly encountered in the North Fork of the St. Lucie River where exposure to low salinities occurs more frequently. Whereas benthic communities collected from the North Fork of the estuary (HR1) are more frequently exposed to higher salinities and are characterized by mysids, amphipods, and polycheates. Both of these communities are common prey for estuarine-dependent juvenile fishes (Diaz and Schaffner 1990).

Table 6.4. Quantitative measures of benthic macroinvertebrate communities collected from the North Fork of the St. Lucie Estuary from 2005 to 2007.

Station	River Mile	Average No. Taxa per 0.02 m^2	Average No. Individuals per 0.02 m^2	Mean Shannon-Wiener index	Surface Sediment (0-2 cm) Organic Content
Prima Vista Bridge	23.1	8.3	197.8	1.1	2.7
Kelstadt Bridge	17.1	10.3	133.3	1.5	2.7
HR1	12.3	4.1	42.2	0.85	18.7

Source: RECOVER. 2007. 2007 System Status Report. Restoration Coordination and Verification Program c/o U.S. Army Corps of Engineers, Jacksonville, FL, and South Florida Water Management District, West Palm Beach, FL. July 2007. pp 5-48 to 58.

6.6.5 Larval and Juvenile Fish Survey (2007)

Icthyoplankton (eggs and juvenile fish larvae) samples were collected on three dates (May 31, June 14, and July 16) during 2007. Sampling locations included (1) Hell's Gate Point, located within the lower estuary (river mile 3.7); (2) HR1, a water quality sampling station within the St. Lucie Estuary (river mile 12.3); (3) Kelstadt Bridge (river mile 17.2); and (4) Prima Vista Bridge (river mile 23.1), both located on the North Fork of the St. Lucie River (**Figure 6.6**).

Surface and bottom plankton samples were collected in the evening in a 500 micron plankton net towed behind a boat for 5 minutes at 2 meters per second. Samples were preserved in 10 percent formalin and all fish larvae and eggs were identified and counted. For the purposes of this document, fish larvae are reported as mean total abundance for all samples collected. Data are only presented from the HR1, Kelstadt, and Prima Vista Bridge sampling locations. For more information the reader is referred to Gilmore (2007), which is provided in **Appendix E**.

Figure 6.9 plots average salinity (surface and bottom) measurements against mean larval fish abundance for each date and sampling location. Results showed highest salinities occurring on May 31, 2007, as a result of low flow conditions associated with the late dry season (2007 also represented an extreme drought year). On that day, salinities measured at HR1, Kelstadt, and Prima Vista Bridge reached 28 psu, 20 psu, and 13 psu, respectively. Mean monthly flows through the Gordy Road Structure during May 2007 equaled 57 cfs. On May 31, fish larvae and eggs collected from HR1 (river mile 12.3) to the Kelstadt Bridge (river mile 17.2) were dominated by eggs from members of the drum family (Sciaenidae) as well as the eggs and larvae of anchovies (primarily *Anchoa mitchelli*). In addition, naked goby larvae were present at low densities between the Kelstadt and Prima Vista bridges (Gilmore 2007).

As natural rainfall events began to increase flows to the North Fork during June (**Figure 6.10**), salinities at the most upstream river station (Prima Vista Bridge) fell to 4 psu, well within the 1 psu to 10 psu range that defines the low salinity zone (**Figure 6.9**). Fish larvae collected from the Prima Vista Bridge on June 14 included the larvae of anchovies, naked gobies, flounder, pipefish (a threatened species), and ladyfish (See **Table B**, **Appendix F**). Downstream at the Kelstadt Bridge and HR1, salinity levels remained within the 17 psu to 25 psu range. The dominant plankton collected from these two sites on June 14 included eggs from the drum family and anchovy eggs and larvae.

By July 16, two natural rainfall pulse events had occurred within the watershed of the St. Lucie River's North Fork (**Figure 6.10**). The first rainfall event began on June 2, 2007, with flows delivered from the Gordy Road Structure reaching 400 cfs over a three-day period and producing a mean monthly flow of about 120 cfs. A second rainfall event occurred on July 4, 2007, with flows peaking at 500 cfs over a period of about a week. Increased rainfall produced a mean monthly flow of about 238 cfs for July. By July 16, these increased flows dramatically reduced salinity levels to 0.5 psu, 1.0 psu, and 10.0 psu at the Prima Vista, Kelstadt, and HR1 sampling locations respectively, as shown in **Figure 6.9**.

July 16 represented the only plankton sampling date when the freshwater/saltwater interface represented by the 1 psu isohaline (and presumably the estuarine turbidity maximum) was located at the Kelstadt Bridge location. Plankton sampling results showed that on this date, the Kelstadt Bridge exhibited an extremely high abundance of fish larvae (mostly gobies) and invertebrates and followed in abundance by anchovy larvae (*A. mitchilli*) (**Figure 6.9** and **Table C, Appendix F**). This observed increase in larval fish abundance corresponded with salinity levels falling within the 1 psu to 2 psu salinity range at the Kelstadt Bridge.

These data indicate that on July 16, maximum larval fish abundance occurred at the Kelstadt Bridge in response to two natural rainfall pulse events (**Figure 6.10**) that moved the 1 psu isohaline downstream between these two bridge locations. It is assumed that these rainfall events provided low salinity conditions that resulted in the formation of an estuarine turbidity maximum and chlorophyll *a* maximum that provided a highly productive nursery area for larval and juvenile fishes as evidenced by the District's plankton sampling efforts.

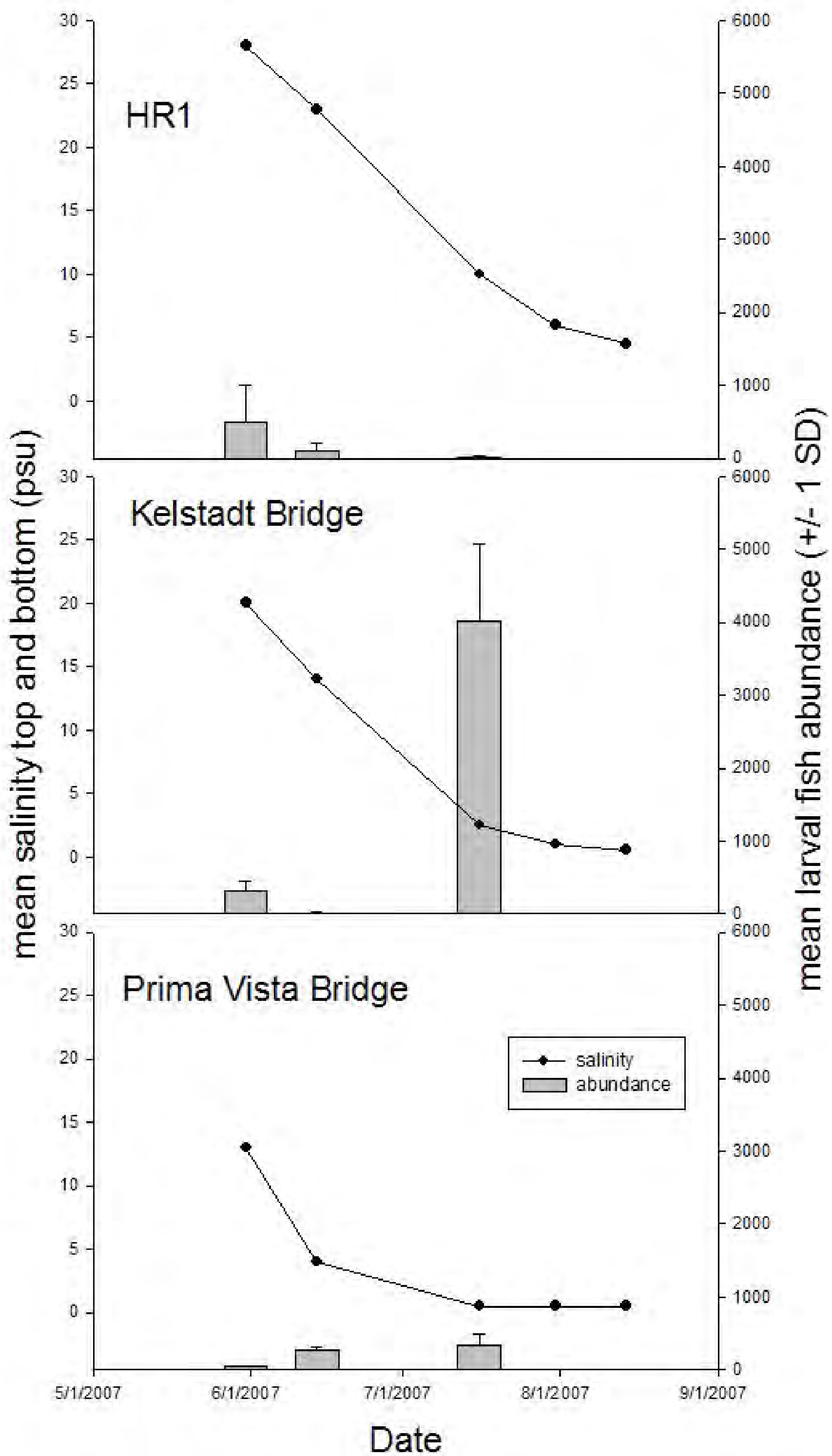

Figure 6.9. Average water column salinity (psu) and mean larval fish abundance recorded at three sampling stations located within the St. Lucie Estuary and River (May–August 2007).

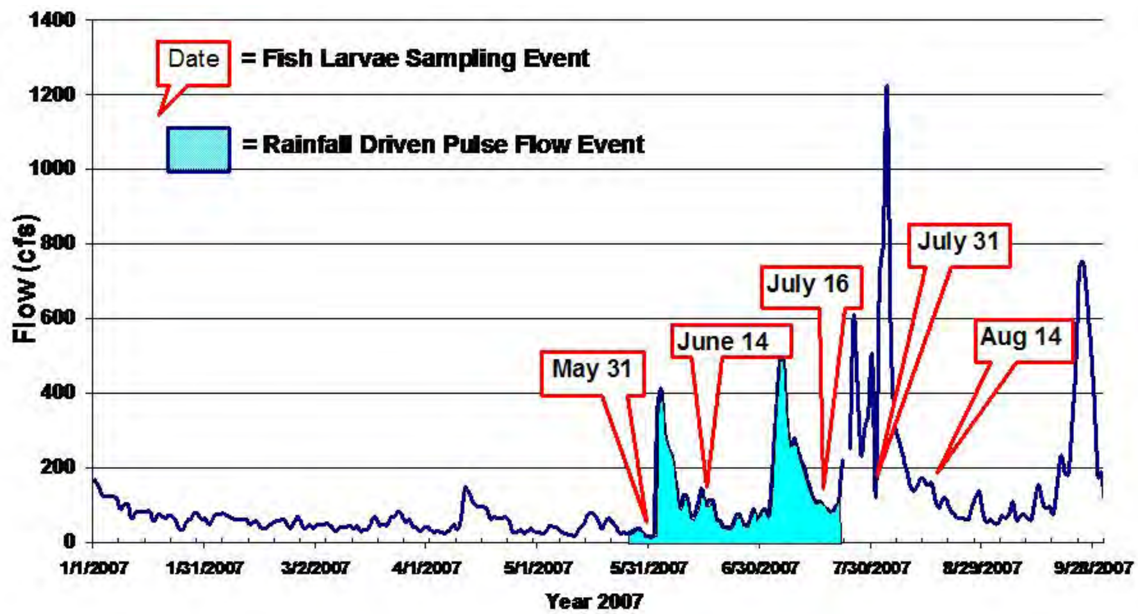

Figure 6.10. Relationship between Gordy Road Inflows and fish larvae sampling dates, January–September 2007.

Another factor that may have contributed to the increased larval fish biomass following these rainfall events is nutrient loading of the estuary. Although water quality is not considered in the development of this water reservation, its role in the establishment of the estuarine turbidity maximum and chlorophyll *a* maximum is recognized. It is likely that nutrients derived from watershed runoff played a role in producing the large biomass of larval fishes and invertebrates observed at the Kelstadt Bridge in July 2007.

Overall these results provide an empirical relationship between flows derived from the Ten Mile Creek Basin (Gordy Road Structure), salinity, and estuarine productivity that characterize the low salinity zone. The greatest fish larvae (mostly gobies and bay anchovies) and invertebrate abundance occurred within the North Fork of the St. Lucie River at the Kelstadt Bridge (river mile 17.2) when the freshwater/saltwater interface (1 psu isohaline) was present at that location.

Review of the literature shows that predatory fish species, such as sand trout, spotted sea trout, ladyfish, tarpon, and snook, found in the downstream St. Lucie Estuary are opportunistic feeders of small fishes and crustaceans. Both naked gobies and bay anchovies represent important forage species for predatory fish found within the St. Lucie Estuary (pers. comm., Grant Gilmore). Gobies have also been identified as important forage fish for recreational and commercial fishes found in estuaries along Florida's west coast (Carr and Adams, 1973), the Gulf of Mexico (Nelson 1992), Texas (Pearson 1929, Gunter 1945), and Virginia (Wass and Wright 1969). Due to their abundance and small size, bay anchovies have also been identified as an important prey species for recreational and commercial fish species found within the Gulf of Mexico (Robinette and Shanks 1983, Scharf et al. 2002, Sheridan 1978).

6.7 Section Summary

1) A combination of the valued ecosystem component (USEPA 1987) approach and the habitat overlap concept (Browder and Moore 1981) was used to focus on critical estuarine habitat needed to protect fish and wildlife within the North Fork. Together, they formed the basis for relating freshwater releases from the upstream watershed to the selected valued ecosystem component (the low salinity zone) and other estuarine resources.
2) Based on a review of available data and its importance to the St. Lucie Estuary, the low salinity zone was identified as the selected valued ecosystem component for the North Fork of the St. Lucie River. The low salinity zone of an estuary occurs where fresh and saline waters meet with salinities typically ranging from 0 psu to 10 psu. The low salinity zone:
    - Represents a highly productive area that is critical to the life histories of many estuarine and marine organisms, serves as important nursery habitat for larval and juvenile fishes, and provides protection from marine predators.
    - Contains an estuarine turbidity maximum and a chlorophyll *a* maximum that serves as an abundant food source for both zooplankton and benthic invertebrate organisms, which become prey for larval and juvenile fishes.
    - Serves as habitat for a broad array of other estuarine species and represents an important resource in terms of commercial, recreational, and ecosystem value from both the local and regional perspective.
    - Using empirical associations or models, relationships can be established between surface water inflows and the spatial extent and location of the low salinity zone within an estuary with reasonable accuracy.
3) A conceptual model of the low salinity zone and its associated components was presented for a partially mixed estuary such as the North Fork. The model includes an estuarine turbidity maximum and a chlorophyll *a* maximum followed downstream by zones of high abundance of zooplankton and copepods, which serve as feeding "hot spots" for larval and juvenile fishes. Freshwater inputs containing sediments and nutrients help to maintain this highly productive area as a nursery for larval and juvenile fishes.
4) Due to inflow variability, the size and position of the low salinity zone varies seasonally in response to rainfall events. Several dynamic habitats or sub-areas exist within the low salinity zone:
    - The estuarine turbidity maximum typically develops near the freshwater/saltwater interface (defined by the location of the 1 psu isohaline) in response to trapped suspended sediments.
    - A short distance downstream, a chlorophyll *a* maximum forms in response to increased nutrients derived from terrestrial runoff and other sources. Together these two processes provide an abundant food source for zooplankton and benthic invertebrates, which become the primary food source for the development of larval and juvenile fish.
5) Empirical data obtained from the North Fork of the St. Lucie River demonstrated that an estuarine turbidity maximum frequently forms within the river during the dry season near the freshwater/saltwater interface as represented by the 1 psu isohaline. The estuarine turbidity maximum moves up and down the river in response to inflows from the Ten Mile Creek Basin (Gordy Road Structure). In addition, a chlorophyll *a* maximum was also documented to exist

within river. Typically the chlorophyll *a* maximum is located a short distance downstream of the freshwater/saltwater interface at salinities greater than 1 psu.

6) The low salinity zone concept has been applied in a number of studies to establish inflow management recommendations for estuaries. Typically an association of fish larvae and secondary production has been tied to zones that equate to the 1 psu to 2 psu isohaline.

7) The spatial extent and location of existing low salinity habitat was evaluated for the North Fork of the St. Lucie River using a GIS methodology. In terms of habitat quantity and quality, an open water and shoreline area located between the Prima Vista and Kelstadt bridges was identified as preferred low salinity habitat that would best support larval and juvenile fishes.

8) Results of zooplankton sampling within the St. Lucie Estuary and the North Fork of the St. Lucie River showed highest zooplankton species richness occurring in high salinity areas, while low salinity areas supported high zooplankton abundance and low species richness. Highest zooplankton abundance occurred in mid-August 2007 at the Kelstadt Bridge location in association with low salinity conditions (mean salinity near 1 psu). Zooplankton abundance at this location was an order of magnitude higher than the other three sites sampled. Many of the zooplankton species present at the Kelstadt Bridge location were of freshwater origin.

9) Monitoring of benthic macroinvertebrate communities showed the abundance of these communities to be three to five times greater in the North Fork than the downstream estuary indicating that the North Fork represents an important food source for larval and juvenile fish. Benthic communities exposed to freshwater conditions within the river were typically dominated by midge larvae and oligochaete worms, while mysids, amphipods, and polychaetes dominated higher salinity areas in the estuary

10) Sampling of larval and juvenile fish within the North Fork of the St. Lucie River showed a relationship between the location of the 1 psu isohaline and the abundance of larval and juvenile fishes within the river. Highest abundance of fish larvae (mostly gobies and bay anchovies) occurred in July (beginning of the wet season) in association with two rainfall events that moved the 1 psu isohaline downstream to the Kelstadt Bridge (river mile 17.2) when the freshwater/saltwater interface was present at that location.

11) Overall, these results provide an empirical relationship between flows derived from the Ten Mile Creek Basin (Gordy Road Structure), salinity, and estuarine productivity that characterize the low salinity zone within the North Fork of the St. Lucie River as an important nursery area for the early life stages of larval and juvenile fishes.

Section 7.
Application of Models for Determining the Performance Measure and Water Availability

7.1 Introduction

Model application was an integral part of both establishing a salinity performance measure and hydrologic flow target for the North Fork of the St. Lucie River, as well as determining the water made available by the implementation of the Indian River Lagoon – South Project. As explained in **Section 5**, the development of a water reservation for the North Fork of the St. Lucie River involved the use of three mathematical models. To determine the salinity performance measure and hydrologic flow target, the CH3D hydrodynamic model was utilized. To determine the volume of water made available by the project, an integrated modeling framework combining watershed (WaSh), reservoir optimization (OPTI-6), and hydrodynamic (CH3D) models was applied. The general scheme illustrating the modeling application and the relationship to the development of the salinity performance measure, flow target, and determination of water availability is shown in **Figure 7.1**. Detailed descriptions of the models are given in **Appendix C** (WaSh model and OPTI-6 model) and **Appendix D** (CH3D model).

The following discussion describes each model formulation and application. The result of the model application produces (1) a flow target for the North Fork of the St. Lucie River and (2) a daily flow time series for the 2050 Future without Project Condition and 2050 Future with Project Condition. Additionally, salinity time series are produced for both the 2050 Future with and without Project Conditions to construct frequency distributions of relevant isohalines and identify improvements to the North Fork of the St. Lucie River associated with the Indian River Lagoon – South Project. These results are used in **Sections 8** and **9** to determine the amount of water needed to be reserved in the North Fork of the St. Lucie River to protect fish and wildlife.

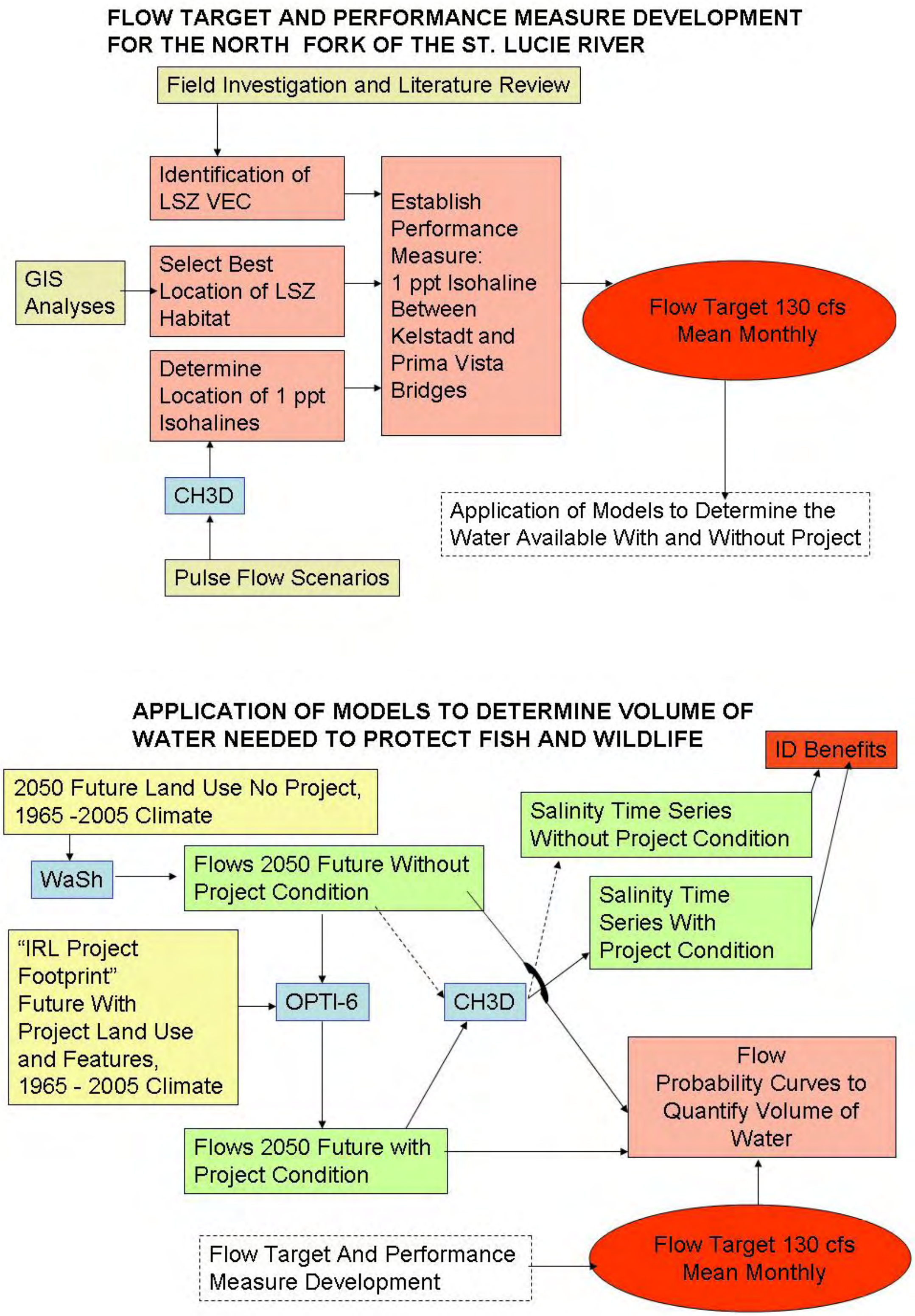

Figure 7.1. Schematic showing application of models to (a) develop the flow target and performance measure and (b) to determine volume of water needed to protect fish and wildlife.

7.2 Determining the Performance Measure and Flow Target for the North Fork

The North Fork of the St. Lucie River contains low salinity habitat that provides a nursery area for larval and juvenile estuarine and marine fishes and shellfish. Based on GIS analysis (**Section 6**), the area between the Prima Vista Bridge (river mile 23.1) and Kelstadt Bridge (river mile 17.2) was identified as the target area for the 1 psu isohaline due to its association with the estuarine turbidity maximum and related ecological benefits, and because it has increased stationary habitat as compared to riverine habitat further upstream (river mile 23 to river mile 32) (**Figure 6.2**). The target volume of water that needs to be delivered from the upstream watershed to maintain low salinity conditions within the target area were determined with the Curvilinear Hydrodynamics Three-Dimensional (CH3D) model.

7.2.1 Hydrodynamic Model Overview

The CH3D model was applied in two separate components of the technical analyses: (1) the development of the performance measure and hydrologic target (**Section 7.2.3**), and (2) the determination of the quantity of water made available by implementation of the project (**Section 7.3.4**). A summary of the formulation is presented here and in further detail in **Appendix D**.

The CH3D model, originally developed by Sheng (1986), is a non-orthogonal grid model capable of simulating complicated hydrodynamic processes including wind-driven, density-driven, and tidal circulation. The non-orthogonal nature of the model enables it to more accurately represent complex geometry in comparison to orthogonal grid models. CH3D contains a robust turbulence closure model for accurate simulation of stratified flows in estuaries and lakes.

The CH3D domain covers the entire Southern Indian River Lagoon, St. Lucie Estuary, South Fork, and North Fork (including the floodplain). Important boundary conditions include hourly surface elevation at the open boundaries, hourly wind and direct rainfall at the surface (based on data from the weather station at the Savannas Preserve maintained by the District), and daily discharge at structures S-48, S-49, S-80, Gordy Road and S-50. The daily discharges at other non-gauged tributaries are simulated with the WaSh model. Ocean salinity is set at a constant 35 psu. Tributary salinity is a constant zero (completely fresh). An average of 1.2 cm per day of groundwater seepage was assumed as submarine groundwater discharge across the entire estuary (Sun 2008, Belanger et al. 2003).

The model was calibrated and verified using nine years of data (1997 to 2005) from the District's five continuous salinity monitoring sites and 12 monthly water quality monitoring stations located throughout the estuary (**Figure 4.7**). The nine-year calibration period covers a wide range of hydrologic conditions including a very dry year (2000) and a very wet year (2004). The calibration stations also cover a significant gradient of tide and salinity from the St. Lucie Inlet to the upstream portion of the North Fork of the St. Lucie River.

7.2.2 Development of the Salinity Performance Measure and Flow Target for the North Fork

The CH3D model was used to simulate steady state salinity conditions within a flow range of 30 cfs to 350 cfs at the Gordy Road Structure. Constant flow boundary conditions were established at the other structures and real tide conditions were simulated for the St. Lucie Inlet. This preliminary evaluation resulted in a series of salinity curves along the North Fork of the St. Lucie River under different flows discharged from the Gordy Road Structure. These steady state salinity curves were used to select a flow range of pulsed flows for further evaluation. Over 10 pulsing scenarios with varying peak flows and total flow volumes were initially evaluated. Results indicated that 400 cfs peak flow occurring on the second and third day during the pulse release effectively pushed the 1 psu isohaline line downstream to the Kelstadt Bridge area.

From the initial pulse scenarios evaluated, three (A, B, and C) were selected for further evaluation. The evaluations of each scenario included the 15-day pulse shown on **Figure 7.2**, delivered twice over a 30-day period. This delivery and mean monthly volume is consistent with two natural (rainfall derived) pulse events that occurred in late May and mid-June 2007 within the North Fork of the St. Lucie River (see **Section 6** and **Figure 6.8**). Thus assuming two pulse releases over a 30-day period, scenarios A, B, and C are equivalent to mean monthly flows of about 130 cfs, 170 cfs, and 100 cfs, respectively, and represent a range of potential target flows. The hydrographs produced for the pulse release scenarios were calculated from a General Curvilinear Dimensionless Equation developed by Neidrauer (1986). The hydrographs consist of three parameters: Tp = the peak period, Qp = the peak flow, and V = the total volume of runoff. The total volumes of runoff include (A) 4,000, (B) 5,000, and (C) 3,000 acre-feet over a 15-day simulation. Peak flows were 400 cfs, 400 cfs, and 250 cfs, all being reached on the third day of each pulse event. These patterns were selected so that the 1 psu isohaline can move quickly downstream to the Kelstadt Bridge area and then retreat slowly upstream to the Prima Vista Bridge. It was assumed that the flows represented by these releases can be delivered over the Gordy Road Structure upon completion of the Indian River Lagoon – South Project.

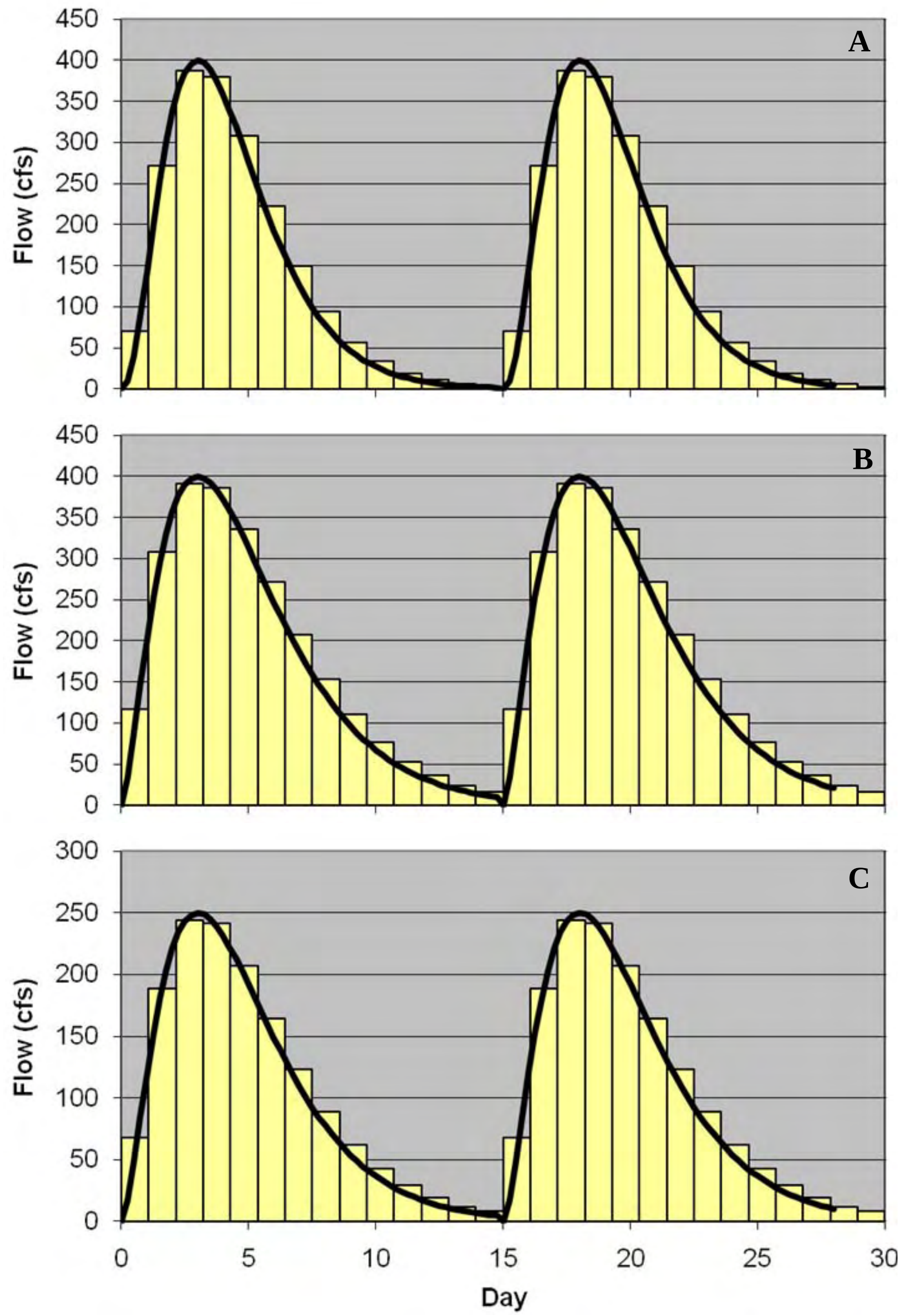

Figure 7.2. Hydrograph for the pulse release at the Gordy Road Structure simulated with CH3D: (A) 130 cfs mean monthly assuming two releases made over a 30-day period, V=4,000 acre-feet, Qp=400 cfs, Tp=3 day; (B) 170 cfs mean monthly assuming two releases made over a 30-day period, V=5,000 acre-feet, Qp=400 cfs, Tp=3 day; (C) 100 cfs mean monthly assuming two releases made over a 30-day period, V=3,000 acre-feet, Qp=250 cfs, Tp=3 day.

7.2.3 Application of the Hydrodynamic Model for Performance Measure Development

To establish the salinity performance measure and flow target, a series of salinity simulations were completed to illustrate the extent and location of the low salinity zone and the 1 psu isohaline (representing in this case the estuarine turbidity maximum) with the CH3D model. Using these simulations, a range of potential target mean monthly flows was established for the North Fork. For these simulations, the model boundary conditions were the same for each inflow point except for Gordy Road, where three inflow scenarios were imposed. Freshwater inflows at other major structures were held at a constant 120 cfs based on an analysis of historic dry season flows over these structures. These structure flows include 30 cfs from S-80 and 90 cfs combined from S-48 and S-49, for a total of 120 cfs from the three structures.

Each CH3D model simulation covered three months starting on January 1, 1999. There was a one-month period for the model to establish initial conditions prior to simulation of each pulse release event. The pulse release started on February 1 and was repeated every 15 days (i.e., twice a month). To present the data from the model simulations, the 1 psu, 6 psu, and 14 psu isohalines were plotted in terms of river mile to represent the extent and range of low salinity conditions under different pulsing scenarios (**Figure 7.3**). This range was selected because it corresponds to research that found spawning fish species under similar conditions (Gilmore 2007).

Several simulations were performed to study the effects of different pulse releases and to define the relationship between pulsed freshwater inputs and the location of the low salinity zone in time and space. Two important trends were observed from these plots. First, the 1 psu isohaline moves back and forth more rapidly in response to freshwater release than the 6 psu and 14 psu isohalines. In other words, the 1 psu isohaline is more sensitive to an increase or decrease in flow relative to the other two isohalines. Secondly, the ultimate downstream location of the 1 psu isohaline depends more on the peak flow rate than on the total flow volume delivered over the 15-day pulsing period.

The location of the 1 psu isohaline ranged from river mile 24 to river mile 17.2 for pulse A, river mile 22.5 to river mile 17.2 for pulse B, and river mile 24.5 to river mile 18.5 for pulse C (**Figure 7.3**). Both pulse A and pulse B push the 1 psu isohaline into the Kelstadt Bridge area (river mile 17.2) at a peak flow of about 400 cfs. This was not so for pulse C (peak flow of 250 cfs), which showed an ultimate downstream location of the 1 psu isohaline line at about river mile 18.5. From these simulation results, it appears that pulse release scenario A, which consists of a mean monthly flow of about 130 cfs (7,993 ac-ft) has the ability to move the 1 psu isohaline to the desired position.

This conclusion for scenario A is further illustrated in **Figures 7.4a**, **7.4b**, and **7.4c**, which show simulated salinity results at the end of Day 0, Day 1, Day 2, Day 3, Day 6, and Day 15. At Day 0, prior to the pulse release, the 1 psu isohaline was slightly upstream of the Prima Vista Bridge (river mile 23). On Day 1, the pulse release quickly moved the 1 psu isohaline downstream. By Day 2, the 1 psu isohaline moved downstream closer to the Kelstadt Bridge (river mile 17.2). On Day 3, the 1 psu isohaline reached the Kelstadt Bridge. As pulse release flows were scaled back on Days 4 through 6, the 1 psu isohaline retreated upstream, but at a slower pace than when it was pushed downstream during Days 1 through 3. By Day 15, the 1 psu isohaline had receded upstream back to the Prima Vista Bridge and another pulse release was initiated on Day 16. The 14 psu isohaline line was located between river miles 10 and 14 during all three pulse events (**Figure 7.3**), indicating that these scenarios have relatively little influence on salinity within the downstream mid-estuary and therefore should not affect downstream (mid-estuary) oyster populations within these simulated flow ranges and base flow conditions.

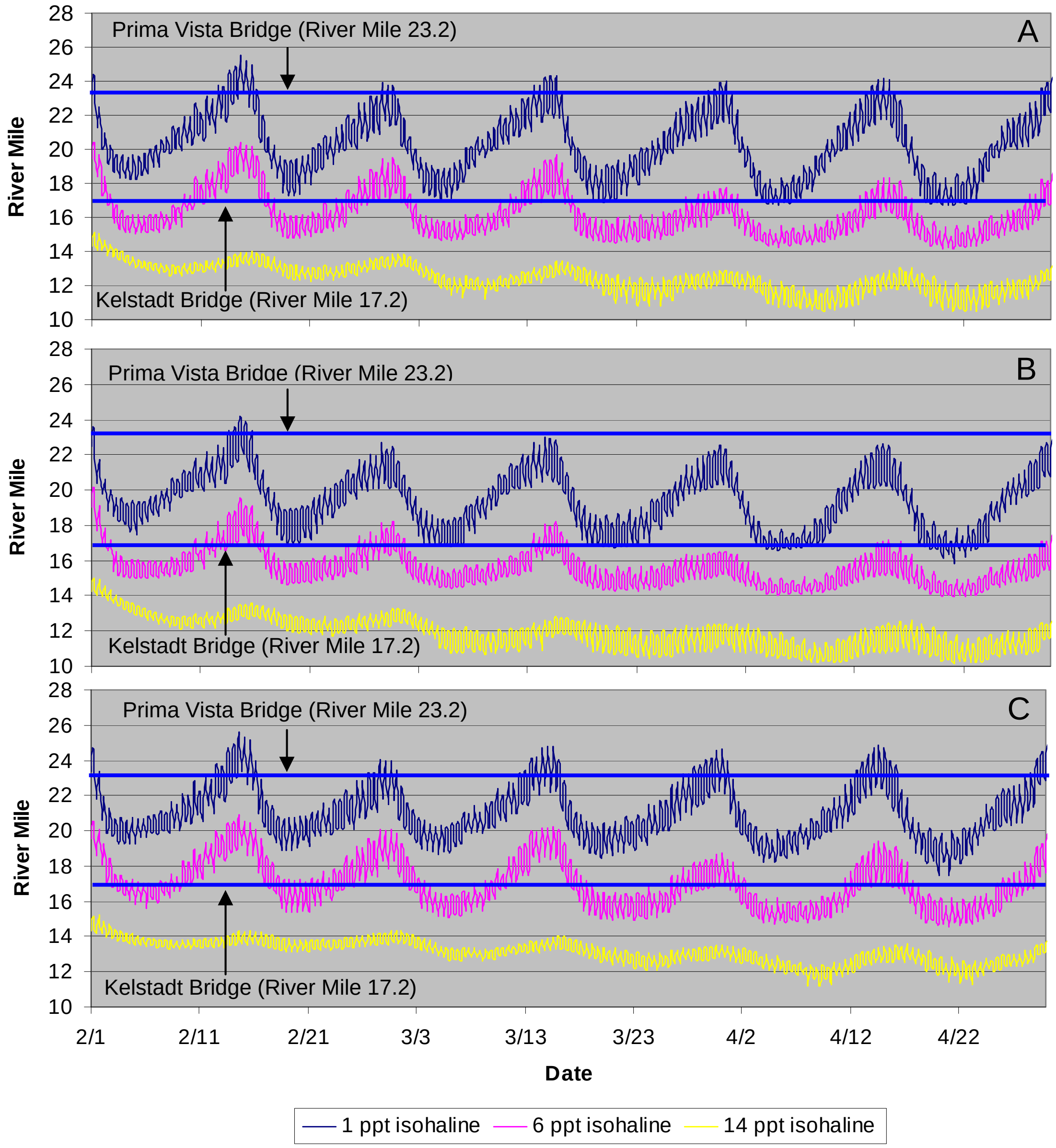

Figure 7.3. Locations of 1 psu, 6 psu, and 14 psu isohalines during the 30-day simulation for (A) 130 cfs mean monthly, V=4,000 acre-feet, Qp=400 cfs, Tp=3 day; (B) 170 cfs mean monthly, V=5,000 acre-feet, Qp=400 cfs, Tp=3 day; (C) 100 cfs mean monthly V=3,000 acre-feet, Qp=250 cfs, Tp=3 day.

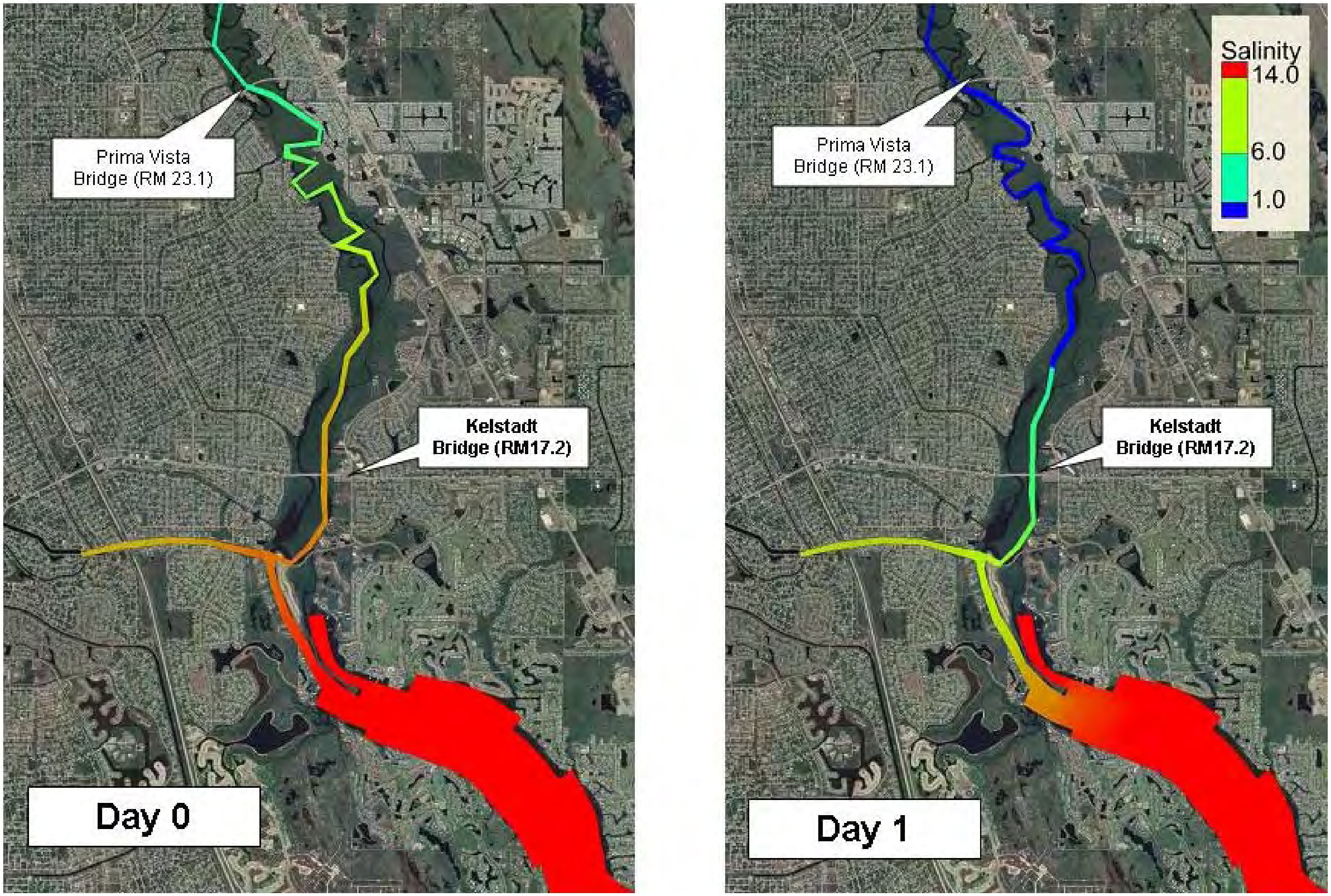

Figure 7.4a. Simulated salinity results for Day 0 and Day 1 using pulse A release flows to the North Fork of the St. Lucie River.

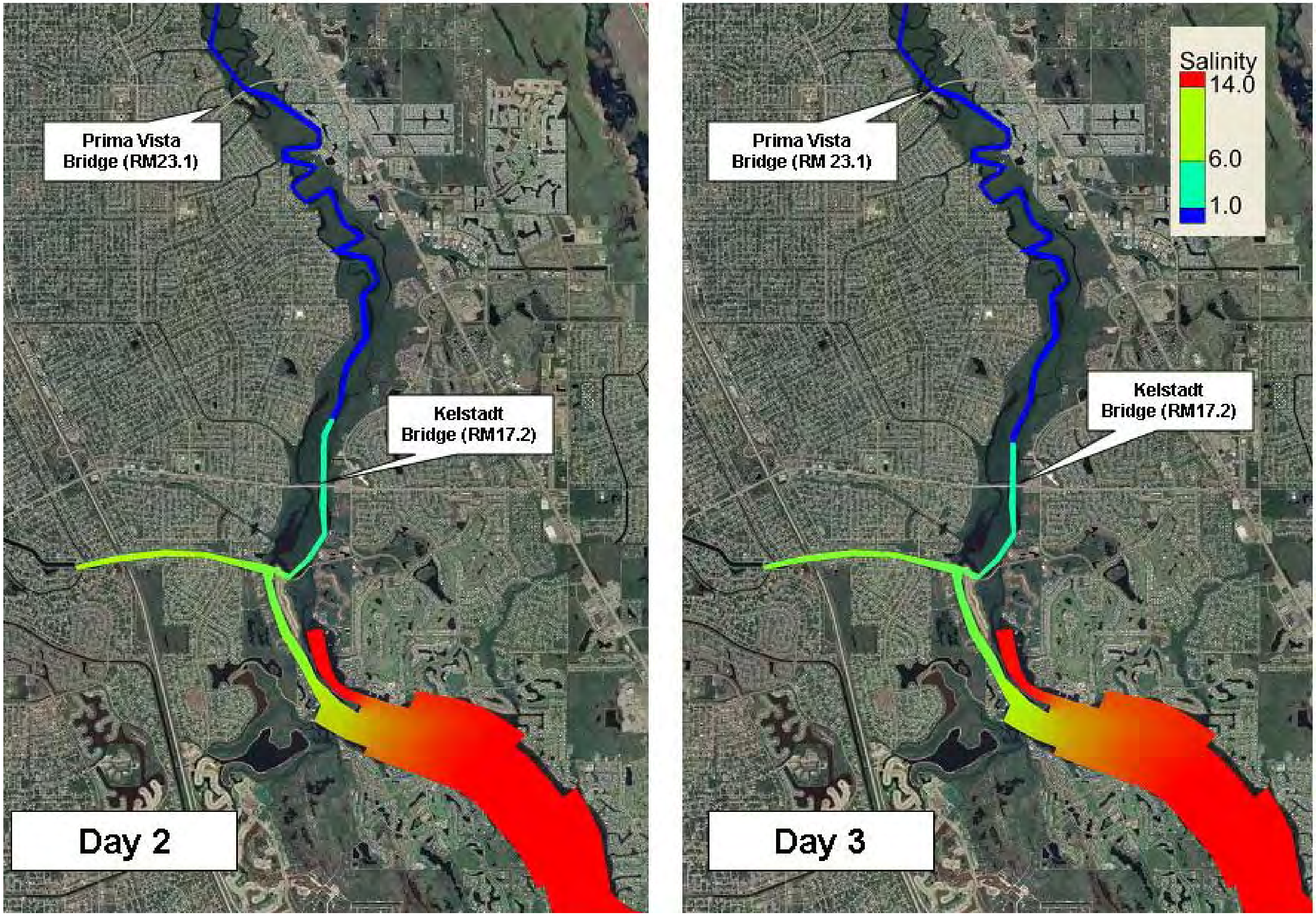

Figure 7.4b. Simulated salinity results for Day 2 and Day 3 using pulse A release flows to the North Fork of the St. Lucie River.

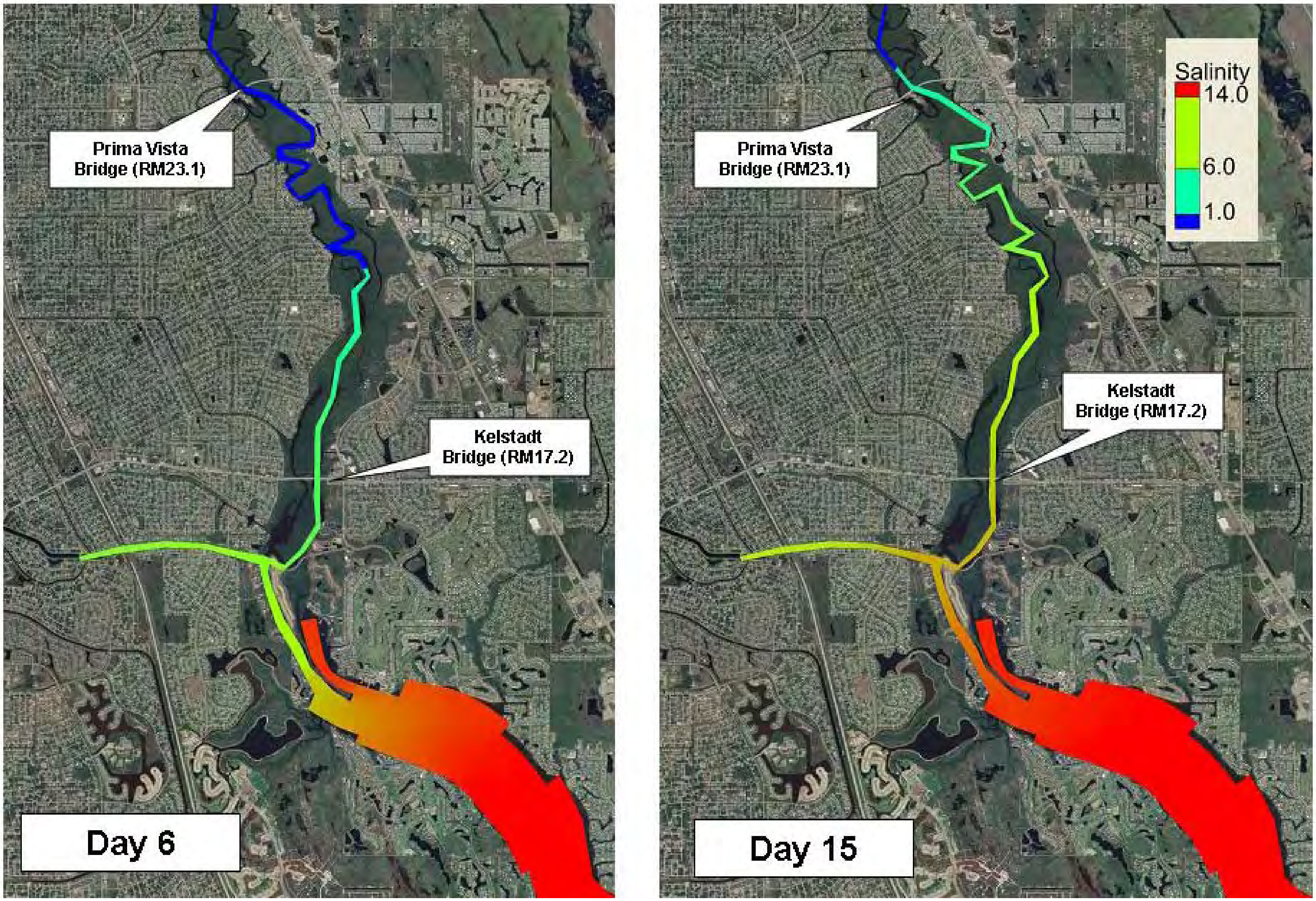

Figure 7.4c. Simulated salinity results for Day 6 and Day 15 using pulse A release flows to the North Fork of the St. Lucie River.

7.2.4 Summary of Proposed Salinity Performance Measure and Flow Target for the North Fork

Maintaining a dynamic distribution of the 1 psu isohaline between the Prima Vista Bridge and the Kelstadt Bridge during the dry season is the salinity performance measure for the North Fork of the St. Lucie River. Modeling analysis indicates this can be achieved with a mean monthly flow target of 130 cfs delivered from the Ten Mile Creek Basin over the Gordy Road Structure, assuming that water can be delivered in a manner consistent with scenario A. It is recognized that some adaptive protocols may need to be established to both achieve and deliver water consistent with the assumptions of the performance measure (**Section 5.1.3**) and to meet the desired ecological benefits of the low salinity zone (**Section 6.2**). An important consideration of this proposed target is that the 14 psu isohaline line was located between river miles 10 and 14 during all three pulse events (**Figure 7.3**). This indicates that these scenarios and their base flow assumptions have relatively little influence on salinity within the downstream mid-estuary (river miles 9.5 to 5.0) and should not affect downstream oyster populations within these simulated flow ranges.

For a discussion of the uncertainty associated with development the above performance measures and the flow target, see **Section 7.5**.

7.3 Identification of Water Availability

To determine the volume of water made available by the project, an integrated modeling framework combining watershed (WaSh), reservoir optimization (OPTI-6), and hydrodynamic (CH3D) models was applied (**Figure 7.1**). This section describes each model formulation and application. The result of the model application produces daily flow time series for the 2050 Future without Project Condition and 2050 Future with Project Condition. Additionally, salinity time series are produced for both the 2050 Future with and without Project Conditions to construct a frequency distribution plot of various isohalines, which were used to identify improvements to the North Fork associated with the Indian River Lagoon – South Project. **Figure 7.5** identifies major Indian River Lagoon – South Project components and elements referred to throughout this section.

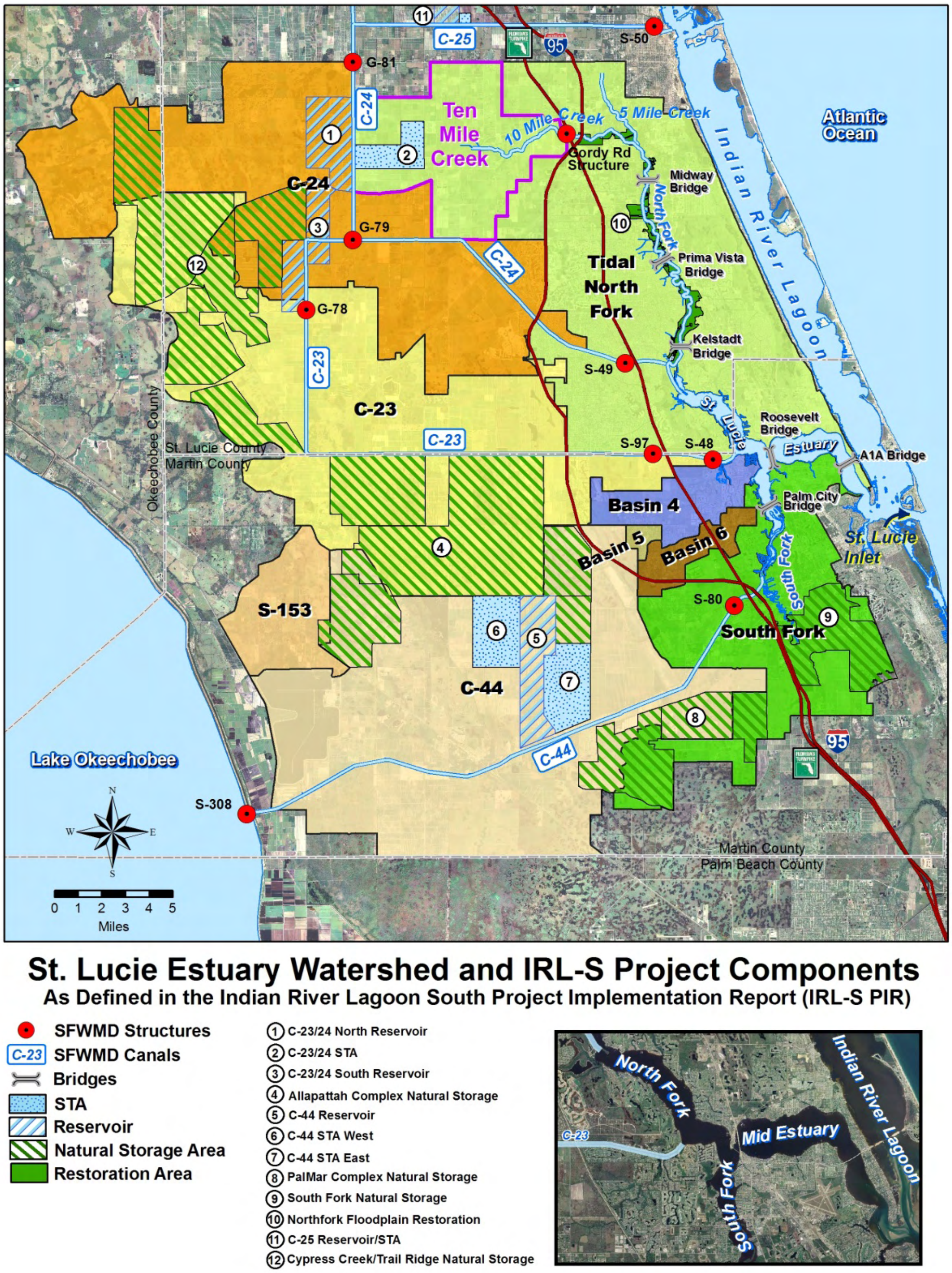

Figure 7.5. Major components of the Indian River Lagoon – South (IRL-S) Project as depicted in the project implementation report (USACE and SFWMD 2004).

7.3.1 WaSh and OPTI-6 Model Formulations

The WaSh model is a physically based watershed hydrologic model, that has the ability to simulate South Florida's unique hydrology (URS 2003). A detailed description of the model is available in **Appendix** C. The WaSh model was implemented in the primary drainage basins (C-24, C-23, C-44 and S-153, Ten Mile Creek, Tidal North Fork, and South Fork), and three minor basins (4 and 5 [Bessey Creek], and 6 [Danforth Creek]) (**Figure 7.6**). Model inputs included primary and secondary basin boundary coverage, polygon features with basin name attributes, hydrography including streams and canals as line or polyline features, the 2000 base land use coverage, soil coverage, and land surface elevations. These data were obtained from the District's GIS database. Using ESRI ArcView software, these GIS data were overlaid to obtain the extent of the model domain along with cell attributes of land use type, soil, canal length and width, and elevation.

Other important inputs were rainfall and evapotranspiration. These data were obtained from the District's South Florida Water Management Model for 1965 to 2000 (SFWMD 1998). The dataset was extended to 2005 with available rainfall and evapotranspiration data from the District's DBHYDRO database. Daily rainfall was disaggregated into hourly rainfall based on an analysis of available hourly rainfall distribution in South Florida.

Hydrologic calibrations for the WaSh model were conducted in three main steps: (1) determination of supplemental irrigation, (2) land use parameterization, and (3) calibration and validation of basin flows. Supplemental irrigation demands and assumptions are presented in **Section 7.3.1.1**. Model parameters specific to representative land use types were determined using a cell version of the WaSh model to match for a target water budget for the particular land use. Measured data collected at major flow structures and selected monitoring stations in the watershed were used for model calibration and validation. The gates at the outfalls of the C-24, C-23, and C-44 Canals (S-49, S-97, S-48, and S-80 Structures) and the Gordy Road Structure on Ten Mile Creek were explicitly represented in the WaSh model and the District operational criteria were applied to configure model parameters. The model was calibrated with data from 1994 to 2000.

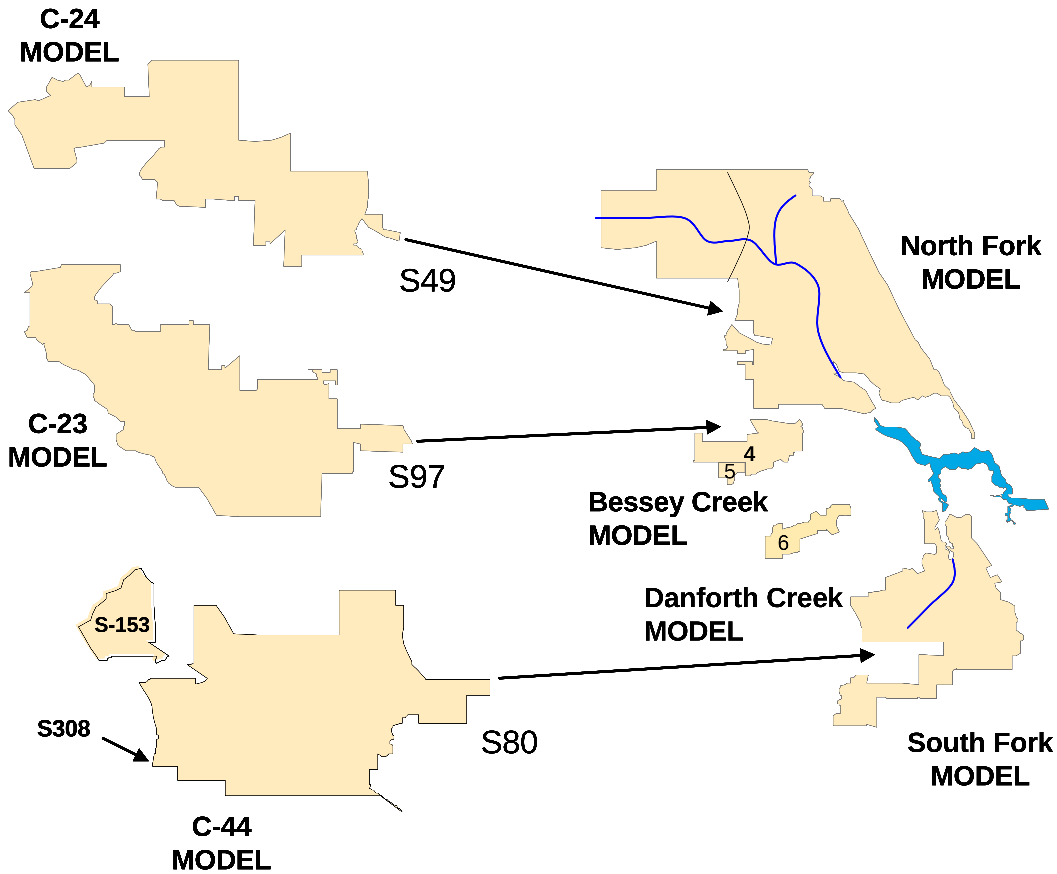

Figure 7.6. WaSh model components and domains.

As defined in the Indian River Lagoon – South Project Implementation Report (USACE and SFWMD 2004), the year 2050 was selected to represent the 2050 Future without Project Condition. A 41-year simulation (1965 to 2005) using the WaSh model was made that predicts expected 2050 land use changes within each basin, termed the 2050 Future without Project Condition (**Figure 7.1**). **Table 7.1** shows the 2050 predicted land use for the 2050 Future with and without Project Conditions for each basin. Comparison of the 2050 Future with Project Condition to 2050 Future without Project Condition land use shows an increase in the natural lands to be restored in basins C-23, C-24, C-44/S-153, Tidal North Fork and South Forks. The reservoirs (12,419 acres), restored natural areas (107,203 acres), and stormwater treatment areas (8,698 acres) constructed within the C-24, C-44, and Ten Mile Creek Basins will utilize almost 26 percent (more than 128,000 acres) of the St. Lucie Watershed. These constructed features account for the differences in land use between the 2050 Future with and without Project Conditions as described in the Indian River Lagoon – South Project Implementation Report and Environmental Impact Statement (USACE and SFWMD 2004).

Table 7.1. Land use acreage related to the Future with and without Project Conditions in the St. Lucie Watershed.

Basin	Forest (ac)	Irrigated Orange Grove (ac)	Pasture (ac)	Urban (ac)	Wetland (ac)	Project Footprint				Total (ac)
						Restored Natural Land (ac)	Reservoir (ac)	STA (ac)	Change by project (%)	
Future (2050) base with project condition										
C-23	6,253	23,156	12,068	11,494	10,734	48,700			43.3%	112,405
C-24	6,560	16,841	15,521	13,412	10,495	18,152	8,554		29.8%	89,535
C-44	11,196	48,102	4,056	4,734	17,920	21,264	3,315	6,000	26.2%	116,586
S-153	2,902	1,541	3,815	517	1,316	3,020			23.0%	13,112
Tidal North Fork	10,992	4,470	29	47,996	9,453	3,366			4.4%	76,305
North Fork - Ten Mile Creek	1,438	22,385	0	1,507	730	0	550	2,698	11.1%	29,308
South Fork	8,826	5,434	2,530	13,896	5,455	12,702			26.0%	48,843
Basin 4, 5 &6	3,550	425	1,513	7,935	1,321	0			0.0%	14,744
Total (ac)	51,717	122,355	39,532	101,491	57,424	107,203	12,419	8,698	25.6%	500,838
Total (%)	10.3%	24.4%	7.9%	20.3%	11.5%	21.4%	2.5%	1.7%		100%
Future (2050) base without project condition										
C-23	11,033	40,858	21,293	20,282	18,940					112,405
C-24	9,348	24,000	22,119	19,113	14,956					89,535
C-44	15,176	65,204	5,498	6,417	24,291					116,586
S-153	3,771	2,003	4,956	672	1,710					13,112
Tidal North Fork	11,499	4,676	30	50,211	9,889					76,305
North Fork - Ten Mile Creek	1,617	25,175	0	1,694	821					29,308
South Fork	10,850	7,160	5,391	17,658	7,784					48,843
Basin 4, 5 &6	3,550	425	1,513	7,935	1,321					14,744
Total (ac)	66,844	169,501	60,800	123,981	79,712					500,838
Total (%)	13.3%	33.8%	12.1%	24.8%	15.9%					100%

The OPTI-6 model is a tool used to optimize the operation of reservoirs and stormwater treatment areas. This model uses a genetic algorithm integrated with fuzzy logic rules and a canal network routing tool. A detailed description of the OPTI-6 model is available in **Appendix C**. Application of the OPTI-6 model requires daily watershed stormwater runoff data as well as irrigation demand on the Floridan aquifer as input data. The WaSh model provided this daily time series (1965 to 2005) under the 2050 Future with Project Condition, which includes proposed natural land restoration conditions and reservoir/stormwater treatment areas for the C-23, C-24, North Fork, and South Fork (including basins 4, 5 and 6) Basins (**Section 5**).

Table 7.2 details the area, depth, and storage capacity of the reservoirs and stormwater treatment areas, diversion pump capacities, and outflow (release) capacities as proposed in the Indian River Lagoon – South Project Implementation Report (USACE and SFWMD 2004). The features of the C-44 Reservoir and Stormwater Treatment Areas are updated based the latest design information. The interbasin transfer capacities are listed in **Table 7.3**. More detailed information on the WaSh and OPTI-6 models is provided in **Appendix C**.

For an explanation of the objectives of the OPTI-6 modeling, see **Section 5.1.4**. Briefly, the monthly flow distribution target for the mid-estuary, particularly for the high flows (monthly mean flows between 2,000 and 3,000 cfs and flows larger than 3,000 cfs) were based on modeling of predrainage conditions within the St. Lucie Watershed (Van Zee 2001). The mean monthly flow target from Ten Mile Creek to the North Fork of the St. Lucie River is 130 cfs delivered over the Gordy Road Structure as defined in **Section 7.2**. Supplemental irrigation targets are explained below.

Table 7.2. The reservoirs and stormwater treatment areas implemented in the OPTI-6 model.

Project Feature	Area (acres)	Depth (feet)	Storage (acre-feet)	Maximum inflow capacity (cfs)	Maximum outflow capacity (cfs)
Ten Mile Creek Reservoir and STA in North Fork	829	7.8	6,462	360	200
C-23 Reservoir	4,399	10.1	44,588	900	1,000
C-24 Reservoir and STAs	6,723	7.1	47,481	900	200
C-44 Reservoir and STAs	9,700	5.2	50,246	1,060	550

Refer to **Figure 7.5** for location of project features.

Table 7.3. Reservoir and storm water treatment area inter-basin transfers implemented in the OPTI-6 model.

Project Feature	C-23 and C-24 reservoirs	C-24 STAs to Ten Mile Creek	C-23 Reservoir to C-44 Reservoirs	C-44 to Lake Okeechobee
Transfer Capacity (cfs)	1,000	200	250	20,000
Operation purpose	Equalize storage in reservoirs, limit to capacity of siphon	Maximize flow to TMC	Minimize C-23 releases	Regional water supply

Refer to **Figure 7.5** for location of project features.

7.3.1.1 Irrigation Water Demands

Agricultural irrigation is a major user of water in the St. Lucie Watershed, therefore the irrigation configuration is one of the most important components in the WaSh and OPTI-6 model formulations. Much of the irrigation water comes from the canal system, which is also a means to control water table levels to maximize crop production and reduce flood damages. During the dry season, fresh water is typically in short supply and the canal system is controlled to retain and reuse fresh water for irrigation to the maximum extent possible. It is also common to supplement irrigation using groundwater from the Floridan aquifer. However, data on irrigation application amounts, acreage, and timing are scarce. The sources for irrigation demand in the 2050 Future without Project Condition were determined by analyzing water elevations in the primary canals. Estimation of the amounts of irrigation used by the citrus growers was conducted based on observed daily water levels, daily flow at water control structures S-97 and S-49, and channel cross-sections of C-23 and C-24 (Lin 2001, Aqua-Terra 1996). The daily amount withdrawn was estimated by the daily stage difference and the stage-area-volume relationship derived from the channel cross-section. This amount was then increased by 30 to 40 percent (SFWMD 1998) to cover the additional water withdrawn from the Floridan aquifer.

The WaSh model assumes that approximately 70 percent of the irrigation demand is supplied by the canal system and shallow aquifers. The remaining 30 percent of demand is obtained from the deeper Floridan aquifer, which is considered an external source in this modeling application, and is termed "supplemental irrigation water supply demand." With adjustment of the evapotranspiration coefficients and supply parameters, an annual average of approximately 15 inches of demand with a 70/30 split for canal and external supply was obtained as the target for citrus groves in the watershed.

In the OPTI-6 model, for the 2050 Future with Project Condition, the supplemental irrigation demand is met with available water stored in reservoir/stormwater treatment areas. A one-in-ten failure probability (10%) is set as the target to meet the supplement irrigation water supply demand from the Indian River Lagoon – South Project. On each specific day, if the total of reservoir/stormwater treatment area available water, interbasin transfer flow, and canal flow is less than the supplemental irrigation demand, the supplement irrigation water supply is not met and the day is flagged as a “supplemental irrigation water supply failure day.” The reservoirs and stormwater treatment areas play an important role in providing supplemental irrigation water supply under the 2050 Future with Project Condition.

Section 7.4.2 presents the results from WaSh and OPTI-6 model simulations for the 2050 Future with Project Condition and the 2050 Future without Project Condition to provide supplemental irrigation demand within the St. Lucie Watershed.

7.3.2 Application of WaSh and OPTI-6 Models to Identify Available Water

The WaSh model was used to simulate the freshwater inflows and irrigation demand to produce the 2050 Future with and without Project Condition flow time series (**Figure 7.1**). This flow time series was further used to help quantify water made available by the project (**Sections 8** and **9**). The flow time series was used as input to the OPTI-6 model to simulate the freshwater flows delivered from the watershed under the 2050 Future with Project Condition. A 41-year period of record (1965 to 2005) consisting of daily freshwater flows was simulated to provide the wide range of climatic conditions characteristic of southern Florida. Results from the OPTI-6 model were inputted into the CH3D hydrodynamic model to produce salinity frequency distributions of various isohalines (1, 5, 14 psu) that were used to identify improvements associated with the project conditions (**Figure 7.1**).

Model results show that at the watershed scare there is an overall decrease in peake freshwater flows delivered to the St. Lucie Estuary from most basins in the 2050 Future with Project Condition. However, as expected with the rerouting of flows to the North Fork proposed by the Indian River Lagoon – South Project, the 2050 Future with Project Condition shows increased annual flows through the North Fork (Gordy Road Structure) relative to the 2050 Future without Project Condition (**Table 7.4**). The monthly flows over the Gordy Road Structure under the 2050 Future with and without Project Conditions as determined from WaSh and OPTI-6 modeling are shown on **Figure 7.7**. This analysis assumes the reservoir operation rules generated by the OPTI-6 model. With the enhancement of interbasin transfer of water from the C-23 and C-24 Reservoirs and Stormwater Treatment Areas to the North Fork via Ten Mile Creek as simulated by the 2050 Future with Project Condition, the mean monthly flow over the Gordy Road Structure exceeds 130 cfs over 90 percent of the time over the 41-year period. It is only during extreme dry conditions, such as 1977, 1981, 1989-1990 (about once every 10 years), that this target is not met.

Table 7.4. Summary of the average annual and average daily flows for the 2050 Future with and without Project Condition. The analysis represents inflows from the St. Lucie Watershed only and does not include Lake Okeechobee inflows.

Basins/Water Management Structures	2050 Future without Project				2050 Future with Project			
	Average Annual Flows		Average Daily Flow	PCT	Average Annual Flows		Average Daily Flow	PCT
	cfs	ac-ft	cfs	%	cfs	ac-ft	cfs	%
Tidal North Fork (U)	68,887	136,637	189	21.0	67,473	133,833	185	25.4
C-23/S-97	66,763	132,424	183	20.4	17,633	34,975	48	6.6
C-24/S-49	59,341	117,703	163	18.1	26,577	52,715	73	10.0
South Fork + Basins 4, 5, 6 (U)	57,720	114,488	158	17.6	41,091	81,504	113	15.4
C-44 & S-153/ S-80	44,360	87,988	122	13.5	47,646	94,506	131	17.9
Ten Mile Creek/ Gordy Rd.	30,794	61,080	84	9.4	65,594	130,106	180	24.7
Total Inflows	327,865	650,320	898	100	266,014	527,639	725	100

U= uncontrolled flows

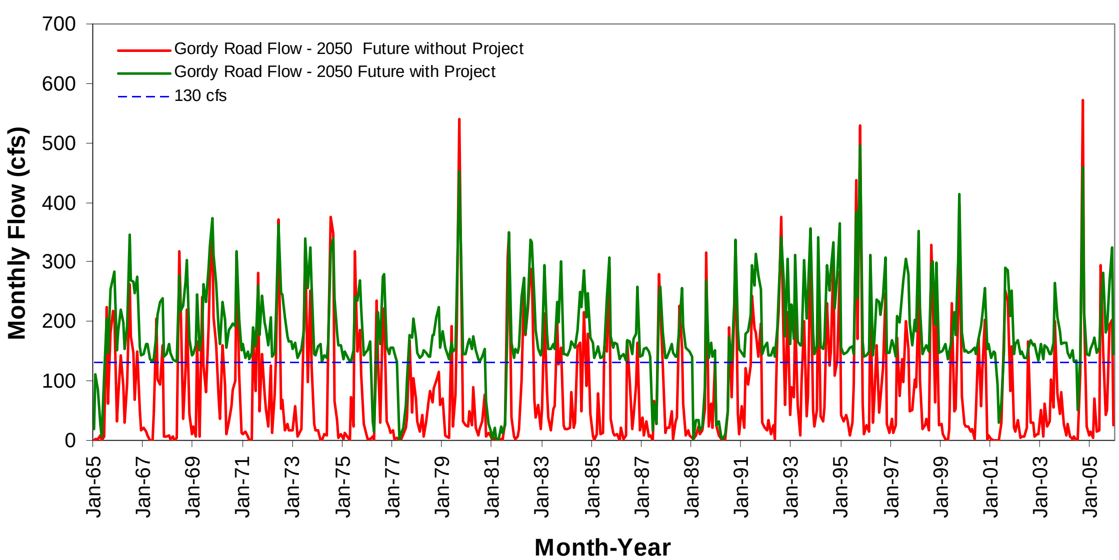

Figure 7.7. Ten Mile Creek flow comparison between 2050 Future with and without Project Conditions as simulated with WaSh and OPTI-6. Note these were modeled with a constant mean monthly 130 cfs flow and not as a pulsed flow.

7.3.3 Hydrodynamic Model Formulation

The CH3D model was applied in development of the performance measure and hydrologic target in **Section 7.2.** The model also was applied to quantify the expected improvements of water delivered by the Indian River Lagoon – South Project. For this application, the CH3D model utilized the daily flow time series produced from the WaSh and OPTI-6 models under the 2050 Future with and without Project Conditions, which included climatic information for the 41-year period and future land use assumptions as previously described. Flows produced by WaSh and OPTI-6 models were used as boundary conditions for the CH3D model at the major inflow control structures including S-97, S-49, S-80, and Gordy Road. Runoff, generated by the WaSh model, from the Tidal North Fork and South Fork were treated as distributed lateral inflow in the hydrodynamic model.

To make the long-term simulations, the tidal boundary condition at the ocean was also needed. Since there are no such long-term records for either the St. Lucie Inlet or the more northern Ft. Pierce Inlet, the tidal boundary conditions were estimated by combining harmonic tide and sub-tidal low frequency motion estimated using surface elevation data at a known remote location. **Appendix D** provides the details of the procedure used to generate the tidal boundary conditions for this model application.

7.3.4 Application of the Hydrodynamic Model to Identify Available Water

The CH3D hydrodynamic model was applied to determine the salinity distributions given the target flows to identify the benefits of increased flow during the dry season. For this purpose, frequency distribution curves were produced for the 1 psu, 6 psu, and 14 psu isohalines along the North Fork of the St. Lucie River for the 2050 Future with and without Project Condition scenario runs (**Figure 7.8**). To develop the frequency distribution curve, salinities were simulated for each river mile of the North Fork. For a particular location at certain river miles, if an isohaline occurred during a day in the simulation period, that day was counted into the frequency for that location. Thus, the frequency at a particular location is actually the total number of days the isohalines crossed that location during the 41-year simulation period. For all three isohalines, increased flow over the Gordy Road Structure under 2050 Future with Project Condition shifted the peak frequency about two miles downstream along with a significant increase in the total number of occurrences during the dry season. This is clearly shown for the 1 psu and 6 psu isohalines (**Figure 7.8**). In addition, over 90 percent of the 1 psu and 6 psu isohaline occurrences are downstream of river mile 16. The model predictions show that excess flow (i.e., mean monthly flows greater than 170 cfs with daily flows greater than 400 cfs) will push the 1 psu isohaline further downstream, which is outside of the target area.

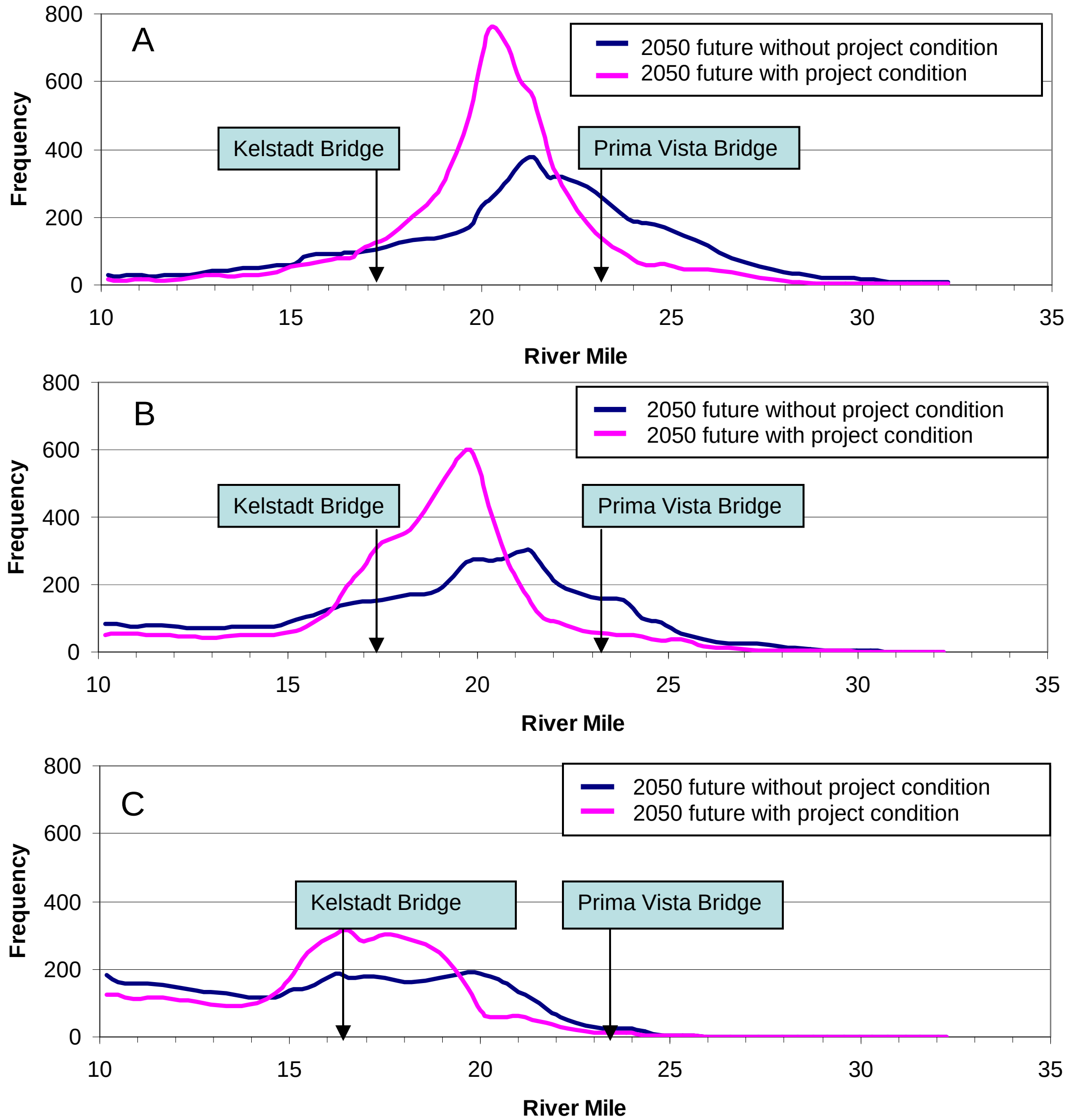

Figure 7.8. Frequency of occurrence of (A) 1 psu, (B) 6 psu, and (C) 14 psu isohalines in the North Fork under the 2050 Future with and without Project Conditions as determined using the CH3D hydrodynamic model.

7.4 Evaluation of Indian River Lagoon – South Project Performance

7.4.1 Mid-Estuary and Oyster Habitat

One of the expected effects of the Indian River Lagoon – South Project is the restoration of approximately 900 acres of oyster habitat within the mid-estuary between the U.S. 1-Roosevelt Bridge (river mile 9.5) and the A1A Bridge (river mile 5.2). This will be achieved by constructing several aboveground reservoirs in the watershed to capture, store, and attenuate damaging high volume inflows. As part of the model evaluation, additional analyses were conducted to ensure that water made available by the project to maintain the low salinity zone within the North Fork of the St. Lucie River also will meet the Indian River Lagoon – South Project performance measure of enhancing oyster habitat within the mid-estuary.

7.4.1.1 Salinity and Flow Performance Measure and Target to Protect Oysters within the Mid-Estuary

Previous biological research and salinity modeling conducted by the SFWMD (e.g., Haunert 1987, Hu 1999, Haunert and Konyha 2004) led to the development of the "salinity envelope" concept for protection and restoration of oysters in the St. Lucie Estuary. This understanding formed the basis to define a favorable range of watershed mean monthly inflows ranging from 350 to 2000 cfs. This flow range corresponds to a salinity range of about 8 psu to 25 psu at the Roosevelt Bridge and was used in the Indian River Lagoon – South Project as salinity performance measures to ensure the protection of oyster communities within the mid-estuary. In general, salinities less than 8 psu create considerable physiological stress on oysters, while salinities higher than 25 psu tend to increase predation from marine organisms and greater prevalence of the disease-causing organism *Perkinsus marinus* (Dermo) (Kennedy et al. 1996, Volety et al. 2003). In the St. Lucie Estuary, increased predation has not been documented at high salinities, though Wilson et al. (2005) demonstrated that the prevalence of oyster disease has a propensity to increase at these higher salinities.

Using the salinity envelope concept, the Indian River Lagoon – South Project established the following hydrologic targets based on a frequency distribution of mean monthly inflows derived from a predainage model of the watershed (Van Zee 2001). These flow targets, as presented in the St. Lucie Watershed Protection Plan (SFWMD et al. 2008), are as follows:

- Flows less than 350 cfs, occurring 47.9 percent of the time or less
- Flows between 350 and 2,000 cfs, occurring 46.0 percent of the time or more
- Flows between 2,000 and 3,000 cfs, occurring 4.8 percent of the time
- Flows greater than 3,000 cfs, occurring 1.3 percent of the time

7.4.1.2 Evaluation of Project Performance

To evaluate project performance using the quantity of water to be reserved for the protection of fish and wildlife within the North Fork of the St. Lucie River, the 41-year simulations of daily freshwater inflows and salinity for the 2050 Future with and without Project Conditions produced by the WaSh/OPTI6/CH3D models were compared to salinity envelope targets developed for the mid-estuary. For the long-term salinity simulation, flows produced by WaSh and OPTI6 models were used as boundary conditions. Long-term tidal boundary conditions were generated by combining harmonic tide and sub-tidal low frequency motion estimated using surface elevation data at a known remote location as described in **Appendix D**.

The predictions generated by the 2050 Future with Project Condition greatly reduce the number of months with flows less than 350 cfs and larger than 2,000 cfs (**Table 7.5**). Specifically, under the Future without Project Condition, there are 155 months with flows less than 350 cfs, 39 months with flows between 2,000 cfs and 3,000 cfs, and 15 months with flows larger than 3,000 cfs. Under the 2050 Future with Project Condition, the number is reduced to 144 months with flows less than 350 cfs, 22 months with flows between 2,000 cfs and 3,000 cfs, and 5 months with flows larger than 3,000 cfs. The performance of the 2050 Future with Project Condition meets or exceeds the Indian River Lagoon – South Project targets originally developed for the mid-estuary.

Table 7.5. Monthly inflow distribution based on model simulation for the period from 1965 to 2005 under Future without and with Project Conditions.

Project Condition	Flow Range			
	<350 cfs	350-2000 cfs	2000-3000 cfs	>3000 cfs
PIR Target for the Mid-estuary	< 47.9%	> 46.0%	4.8%	1.3%
2050 Future without Project Condition	32 % (155)	58% (283)	8% (39)	3% (15)
2050 Future with Project Condition	29 % (144)	65% (321)	4% (22)	1% (5)

*Number in parenthesis refers to months of the particular flow range during the 41-year simulation period.

Table 7.6 illustrates how the proposed quantity of water to be reserved to protect fish and wildlife in the North Fork of the St. Lucie River will affect salinity conditions within the mid-estuary. In general, exposures to low salinities are associated with strong storm events that are short in duration, while exposures to salinities greater than 25 psu are associated with long-term rainfall deficits (droughts) that last for several months. Under the 2050 Future without Project Condition, the models identified 81 months with a mean salinity greater than 25 psu and 39 months with a mean salinity less than 8 psu. Under the 2050 Future with Project Condition, these values are reduced to 38 months and 11 months, respectively. The improvement in salinity conditions in the mid-estuary is associated with the reduction of the number of months with mean monthly flows less than 200 cfs and larger than 2,000 cfs under the project condition. Thus reserving water for the low salinity zone in the North Fork also has the potential to enhance oyster habitat for both low salinity and high salinity regimes in the mid-estuary, thereby maintaining overall Indian River Lagoon – South Project objectives.

Table 7.6. Monthly salinity distribution based on model simulation for the period form 1965 to 2005 under Future with and without Project Conditions.

Project Condition	Oyster Salinity Tolerance Ranges		
	< 8 psu	8~25 psu	>25 psu
2050 Future without Project Condition	8% (39)	76% (372)	16% (81)
2050 Future with Project Condition	2% (11)	90% (443)	8% (38)

*Number in parenthesis refers to months of the particular flow range during the 41-year simulation period

7.4.2 Supplemental Irrigation Supply

Another objective of the Indian River Lagoon – South Project is to provide reservoir storage to reduce demands on the Floridan aquifer. The reservoir/stormwater treatment area plays an important role in providing supplemental irrigation water under the 2050 Future with Project Condition. It provides about 80 percent of the supplemental irrigation water supply in the C-23, C-24, and Ten Mile Creek Basins, and more than 50 percent in the C-44 Basin (**Table 7.7**).

To evaluate the performance of the project in providing the supplemental irrigation water, the OPTI-6 model was used to calculate the percent of days when the project features, mainly the reservoir system, failed to provide supplemental irrigation demands. The objective set in the OPTI-6 model was 10 percent, which is roughly equivalent to once every 10 years. **Table 7.8** shows that the OPTI-6 model is capable of providing the optimized operation for reservoir/stormwater treatment area and interbasin transfers to meet the supplemental irrigation water demand on the Florida aquifer at the specified reliability.

Table 7.7. Supplemental irrigation demand from the Floridan aquifer and actual water provided by reservoir/stormwater treatment area.

Reservoir/STA	Basin Supplemental Irrigation Demand (ac-ft)	Actual Water Supply Provided for Supplemental Irrigation from Reservoir/STA	
		(ac-ft)	(%)
C-23	16,000	12,800	80%
C-24	8,900	7,000	79%
TMC	8,200	6,400	77%
South Fork	0.0	0.0	0.0
C-44	29,200	15,500	53%

Table 7.8. Failure frequency for the project to supply supplemental irrigation demand.

Basin	Frequency of Irrigation Failure
C-23	2.8%
C-24	3.0%
TMC	1.5%
South Fork	0.0%
C-44	10.0%*

* Acceptable risk level for supplemental irrigation water supply is 1-in-10 (10%)

7.5 Sources of Uncertainty

7.5.1 Performance Measure and Target Development

Several sources of uncertainty are associated with performance measure and target development. One area of consideration is that the hydrologic target for the North Fork of the St. Lucie River is based on a pulsed flow regime that has been converted to a mean monthly flow target. The subsequent modeling presented comparing the 2050 Future with and without Project Condition does not utilize pulsed flow as input (**Figures 7.7** and **7.8**) and therefore does not specifically assess the target as proposed.

An additional consideration inherent both in the hydrologic target and the salinity performance measure is nutrient loading. Although water quality is not considered in the development of this performance measure, its role in the establishment of the estuary turbidity maximum and chlorophyll *a* maximum is recognized. It was assumed that nutrient loading should not be a major concern because the additional flows directed to the North Fork of the St. Lucie River originate from the C-23/C-24 Reservoirs and Stormwater Treatment Areas.

Another consideration is that to be ecologically beneficial, pulse releases should mimic natural flow patterns (Poff et al. 1997, Richter et al. 1997, Estevez 2002), including amount of flow, frequency of occurrence, and nutrient loadings. To be consistent with natural dry season patterns, it is not anticipated that pulse releases be made every month throughout the dry season. Additionally, seasonal timing or coordination with annual climatic conditions (i.e., rainfall events or drought), as well as biota needs (**Table 6.1**) will likely be important factors in the implementation of pulse releases.

Pulses may also be desirable to protect fish and wildlife at times other than the dry season such as under drought conditions or if the wet season onset is delayed. Such operational protocols are not addressed as part of the water reservation rule development analysis. Greater understanding of the mechanisms controlling estuarine productivity as it relates to pulsed releases will require operational flexibility coupled with environmental monitoring. Upon implementation of the water reservation, assessment will be ongoing to address these uncertainties. Monitoring of the location of the 1 psu isohaline and associated biota in the North Fork will be specified in the detailed design phase of the Indian River Lagoon – South Project (see **Section 7.6**). New information may also be incorporated in periodic rule development (see **Section 9.2**).

7.5.2 WaSh Model

The WaSh model is a distributed hydrological model that usually has three types of associated uncertainty: (1) model representation, (2) model parameter, and (3) model input. The uncertainty involved with the WaSh modeling results can be a collection of these factors. As presented in **Appendix C,** the WaSh model is calibrated with data from 1994 to 2000. The performance of the daily flow calibration was good with values of the Nash-Sutcliffe coefficient and the coefficient of determination ranging from 0.6 to 0.7.

The deviation of volume, which quantifies the difference in observed and predicted water volume, are also used to evaluate model performance. The computed deviation of volume falls in the range of -8 percent to 12 percent during the calibration periods. This section describes possible sources of model uncertainty that may be causing these errors.

The representation of uncertainty refers to the difference between the model and the real system. It is important that a hydrologic model represents the physics of a real hydrological system. Unrealistic model structure and misrepresentation of the real system may result in significant bias in the resulting simulation. The WaSh model employs widely used representations of surface water, groundwater, and canal routing equations including: (1) the HSPF PWATER module (surface water hydrology), (2) the standard MODFLOW equations, (groundwater hydrology), and (3) full dynamic wave equation (primary canal flow routing). Groundwater recharged by rainfall and seepage into canals are simulated through the interactions among the three hydrologic representations (**Appendix C**).

The source of uncertainty may come from the numerical scheme used to solve mathematic equations in the model and selecting appropriate time steps and space steps in the model development. WaSh uses an hourly time step for PWATER, a daily time step for the groundwater model, and a 15-minute time step for the canal routing model. These time steps are considered to be appropriate for watershed modeling.

Another source of uncertainty stems from the representation of the water management practices in the watershed. The size and operation of drainage and irrigation pumps, canals, and water control structures are not all represented in the model explicitly. This may have contributed to the uncertainty of modeling the hydrology on a daily time step.

The sources of model parameter uncertainty include the model developer's background, understanding of the watershed system, and model calibration effort. Studies have revealed that not accounting for parameter heterogeneity can exert a strong influence on the predictive capability of the model (Jakeman et al. 2006). WaSh has over 50 model parameters that were calibrated manually during the model development process.

The uncertainty of model inputs can be the most significant source of uncertainty involved in model simulation. Model input uncertainty is associated with the temporal and spatial variability of the inputs of rainfall, potential evapotranspiration, land use, land cover, soil, tertiary and primary canal features, boundary conditions (flow and stage), and aquifer features. The input data of the model may not adequately represent the accuracy and variability of these inputs. For example, the spatial variation of rainfall in a basin is simplified in WaSh as a single rainfall input data set obtained through the Thissen polygon method. The error of measured data as model input will also be directly reflected in model simulation results. Effort has been made on meteorological and hydrologic data collection and data quality assurance and quality control to obtain reliable representation of the input variability.

Groundwater Assumptions

Two aquifer systems, the surficial aquifer and the Floridan aquifer, exist within the project area. The WaSh model only includes the surficial aquifer with a no-flow boundary condition assumed between it and the Floridan aquifer system. This assumption is also used in other surficial aquifer models used in the District (e.g., Agams 1992, Butler and Padgett 1995). The uncertainty with this assumption is considered to be low since the two aquifers are laterally continuous, but are vertically separated by several hundred feet of low-permeability sediments. This confining layer consists primarily of clay, dolomite, and micritic limestone, normally encountered between about 150 to 700 feet below the ground surface in the project area. A review of regional groundwater models of the area indicates that the vertical hydraulic conductivity of this confining unit is low, about 0.0005 to 0.00001 feet per day (Sepulveda 2002). Thus, vertical leakage from the Floridan aquifer to the surficial aquifer should be insignificant. However, the Floridan aquifer is assumed to be the source of irrigation water, meeting about 30 percent of the total irrigation demand in the C-23 and C-24 Basins (**Section 7.3.1.1**). For a detailed discussion of the representation of the surficial aquifer in the WaSh model, see **Appendix C**.

Since this modeling is used to produce the flow series for the 2050 Future without Project Condition and are input directly into OPTI-6 to generate the flow series for the 2050 Future with Project Condition, the effect of groundwater is important in modeling these flow time series as well as the comparisons generated from these series. Due to the lack of measured well stage data in the St. Lucie River Watershed, the groundwater boundary condition in the WaSh model is considered as a major source of model input uncertainty. Calibration of groundwater levels was conducted during land use parameterization using MicroWaSh (**Appendix C**) to ensure proper wetland hydroperiod and water levels in major land use types were represented. At the basin level, the major objective of calibration is to match the modeled basin flows with these measured District flow control structures for this model application. Future refinement of the model calibration should include groundwater well data in this watershed.

7.5.3 OPTI-6 Model

OPTI is an optimization model that takes daily flow and irrigation data simulated by WaSh as model inputs. The genetic algorithm driver program used in OPTI-6 is well accepted in the software community and was obtained as freeware from Dr. David Carroll (CU Aerospace, Inc., Champaign, Illinois, http://cuaerospace.com/carroll).

The model itself does not produce flows. Instead, it distributes flows according to the operation rules generated by the model. A water budget check was performed to ensure that flow distributions are balanced at the end of a day. In this regard, the model uncertainty involved with OPTI-6 is extremely small as long as the input data are correct. However, real-time day-to-day operation of the reservoirs and water control structures may not be able to achieve the optimal results produced by OPTI-6.

The OPTI model can be modified to add forecasting functionality to guide day-to-day operations. The operational rules generated by the model can then be incorporated into the real-time operation. Results from the modeling work related to this project indicate that the general operational rule of the C-24 Stormwater Treatment Area is to provide continuous water quality improvement and flow delivery into the Ten Mile Creek Basin year-round when there is water in the reservoirs. The results also suggest that the C-23/C-24 Reservoirs should be operated in a manner that gets them close to their full capacity before the onset of the dry season.

The OPTI-6 model does have limitations. For example, during a dry year when the reservoirs do not have a sufficient amount of water stored to meet the water reservation target during the entire dry season, the OPTI-6 model does not hold back flows for the later part of the dry season, which is when the low salinity zone is most critical for fish larvae and juveniles in the ecosystem. This and other model limitations can be overcome through the operational protocols that will be developed in the future.

7.5.4 Hydrodynamic Model

Model Calibration and Boundary Conditions

In general, the accuracy of numerical model predictions depends on how well the model is calibrated. Based on the calibration results reported in **Appendix B**, the model performance is considered to be satisfactory in the North Fork area. For the North Fork pulsed flow simulation, measured tidal elevations were used at the ocean boundaries. Simulation results suggest that the movement of the isohalines in the low salinity zone is not very sensitive to changes in the tide, assuming average tidal conditions. The root mean square error of tide calibration was less than 0.1 meters and the coefficient of determination ranged from 0.90 to 0.95. For salinity calibration, the root mean square error ranged from 1.32 to 3.23 psu and the coefficient of determination (r^2) ranged from 0.56 to 0.97.

The model simulated both tide and salinity accurately. In particular, the model satisfactorily predicted salinities in the North Fork between the Prima Vista and Kelstadt bridges. The error here should be minor relative to other uncertainties in the model.

Groundwater Input Assumptions

During dry seasons or a drought, groundwater input to the estuary is a significant part of the total freshwater inflow relative to wet conditions (**Section 4**). An accurate quantification of the groundwater input to the system will lead to cost effective planning and project design. In the CH3D model, groundwater input is modeled as a constant rate of 1.2 centimeters per day (cm/day).

Past studies have indicated that groundwater seepage is a significant part of freshwater inflow into the St. Lucie River and were used as a basis to estimate the constant seepage rate used in the CH3D model. Belanger et al. (2003) conducted groundwater seepage meter measurements in the St. Lucie River to quantify the seepage between groundwater and surface water and establish the processes controlling groundwater/surface water interaction. This study determined that the groundwater discharge into the St. Lucie River is controlled by hydraulic gradients and the hydraulic properties of the adjacent aquifer and leakance from the sediment. The average seepage rate was estimated to be 1.3 cm/day. In an updated effort, Belanger et al. (2007) estimated the average groundwater seepage rates to be 1.6 cm/day, the difference being attributed potentially to changes in regional groundwater levels. Unpublished data collected by District staff using a seepage meter, indicate that groundwater seepage rates into the St. Lucie range from 1 cm/day to 2 cm/day (Krupa, unpublished data). District staff also used the CH3D hydrodynamic model to back calculate the groundwater seepage rate into the St. Lucie (Sun 2008). The modeling results indicated that a seepage rate of 1.2 cm/day best matched the salinity gradient during the 2000 drought. This seepage rate is equivalent to about 150 cfs given an estuary surface area of 11.3 square miles, very close to an early back-calculation effort using a one-dimensional model by Morris (1987). An accurate quantification of the groundwater input to the system, particularly on a seasonal basis, is recommended to allow more cost effective planning and project design.

Recirculation of seawater is a significant component of groundwater discharge as indicated by Motz and Sedighi (2009a, 2009b). Cable et al. (2004) used multiple techniques to quantify the total groundwater discharges related to advective fluxes at the sediment-water interface (including recirculated sea water mixed with land-recharged water) in the Indian River Lagoon estuary system. From this work, diffusive and advective benthic fluxes into the lagoon were evaluated using a geochemical tracer. The groundwater discharge rates obtained from these studies are 4 cm/day to 9 cm/day using seepage meters and 3 cm/day to 20 cm/day using geochemical tracers, much larger than the 1.2 cm/day used in the development of this reservation. Martin et al. (2007) further concluded that that the discharge of recirculated seawater was more than two orders of magnitude larger than groundwater discharge from terrestrial sources. For applications in this project, the groundwater seepage rate used in the CH3D model is considered as a net groundwater seepage rate from terrestrial sources with zero salinity assumed as the boundary condition. The uncertainty involved with not considering the recirculation of the seawater in the model is considered to be insignificant since there is no net water exchange with seawater recirculation.

Freshwater Inflows from District Structures

Flows from S-80, S-48, S-49 (**Figure 7.5**), and other structures are another major source of fresh water for the estuary and may be a source of some uncertainty. These flows serve as the inland boundary condition for salinity simulations within the North Fork. The period chosen for the simulation to determine the performance measure and flow target in **Section 7.2** was relatively dry with a total inflow of 120 cfs from the three major canals (C-44, C-23, and C-24). The measured dry season flows from these three canals from 1996 to 2005 averaged about 170 cfs. Thus, the 120 cfs flow assumed for these structures is probably representative of a typical dry season condition, though there are times that flow over these structures can be less. In addition, because of the distance of these structures from the low salinity zone, flow over the Gordy Road Structure is still the predominant factor determining salinity distribution in the North Fork.

7.6 Future Monitoring and Performance Assessment

Development of protocols for performance assessment such as monitoring, adaptive management, or operations plans are not part of the water reservation rule development process. However, the importance of these elements in successful implementation of the water reservation rule are recognized, and will be addressed as part of an Indian River Lagoon – South Project operation plan in the detailed design phase. An adaptive management and monitoring plan will be developed as part of the project operation plan and coordinated within appropriate CERP monitoring and assessment programs. Specific protocols associated with the water reservation for the North Fork of the St. Lucie River are anticipated to address sources of uncertainty related to the performance measure and target development of the water reservation. An adaptive management plan will consider evaluation of the frequency of pulse releases, as well as physical (e.g., salinity and hydrography) and biological measures (e.g., benthic and planktonic) relative to the management of the pulse releases. Data and analyses on naturally occurring pulsed events is currently underway and will continue to be used to determine potential system responses and evaluate the natural frequency of responses prior to water reservation rule implementation. This information will be used to develop a strategy for project implementation and monitoring of biological and physical responses. Additionally, the Water Reservation Rule will be periodically updated and additional or new technical evaluations may be included in revised documentation (see **Section 9.2**).

7.7 Summary and Conclusions

The WaSh model was used to produce the daily time series of freshwater inflows for the 2050 Future with and without Project Conditions. These data were used as the input data for the OPTI-6 model to simulate the freshwater flows delivered from the watershed with projects proposed in the Indian River Lagoon – South Project. A 41-year period of record (1965 to 2005) consisting of daily freshwater flows was simulated to ensure the representation of a wide range of climatic conditions. The daily flows represented by the Future with and without Project Conditions were used as input data for the CH3D hydrodynamic model, which provides salinity estimates.

Results from these models were compared to the salinity performance measure and flow target described in **Section 7.2** to evaluate how much of this flow is required to protect these communities under the Future with Project Condition. Under this condition, mean monthly flows released from the Gordy Road Structure to the North Fork are maintained above 130 cfs for more than 90 percent of the 41-year simulation period. As a result, the frequency that the 1 psu isohaline can be located between the Kelstadt and the Prima Vista Bridges, which is the target location for the low salinity zone, has been significantly increased.

The overall modeling results indicate that the mean monthly dry season flow target of 130 cfs delivered to the North Fork of the St. Lucie River via the Gordy Road Structure will allow the 1 psu to be positioned in the preferred habitat area between the Prima Vista and Kelstadt Bridges assuming these flows are delivered consistent with the pulsed inflow scenario A used to create the target (**Section 7.2.2**). Additional analysis indicates that reserving water for the low salinity zone in the North Fork will also enhance the oyster habitat for both low salinity and high salinity regimes in the mid-estuary. An adaptive management and monitoring plan will be developed as part of the project operation plan to address the sources of uncertainty associated with the performance measures and hydrologic target.

Section 8.
Quantification of Water for
the North Fork of the St. Lucie River

As explained in **Sections 1.3** and **5.1**, quantification of water made available by the project over a represented time and range of hydrologic conditions corresponds to step 4 of the overall technical approach. Based on a review of available field data and its importance to the ecology of the St. Lucie River, the low salinity zone was identified as the valued ecosystem component for the North Fork of the St. Lucie River. This is consistent with the objectives of the Indian River Lagoon – South Project.

To identify a quantifiable amount of flow available for the protection of fish and wildlife, field studies (**Section 6**) and an integrated modeling framework combining the St. Lucie watershed (WaSh), reservoir optimization (OPTI-6), and estuarine hydrodynamic (CH3D) models was applied to (a) determine a flow target for the North Fork of the St. Lucie River and (b) identify the quantity of water needed to protect fish and wildlife (**Section 7**). The CH3D model was used to develop a time series of pulsed freshwater inflows delivered from the Gordy Road Structure to the North Fork of the St. Lucie River that would support establishment of low salinity conditions within the river that will protect larval and juvenile fishes during the dry season (**Section 6**). This time series represented the flow target for the North Fork, which is expressed as a mean monthly flow of 130 cubic feet per second (cfs).

Results of the WaSh/OPTI-6 modeling produced a time series of daily flows representing the 2050 Future with Project Condition that serves as the baseline for flows produced by the Indian River Lagoon – South Project (**Section 7**). This daily time series included a 41-year timeframe (1965 through 2005) that is representative of average, wet, and dry hydrologic conditions within the watershed and was used to determine the quantity of water made available by implementation of the project. This daily time series was converted to mean monthly flow data to match the North Fork flow target.

These data were sorted and ranked from highest to lowest values and presented as volume probability curves for the entire 41-year simulation period as well as for wet and dry season conditions. Volume probability curves indicate the probability (percentage of time equaled or exceeded) that a certain quantity of water is available for fish and wildlife protection as a function of historical rainfall distribution based on the WaSh/OPTI-6 model simulation.

8.1 Flow Target

To identify the quantity of water needed to protect fish and wildlife, a salinity performance measure and a flow target for the North Fork were developed. The identified performance measure is to maintain a dynamic distribution of the 1 psu isohaline between the Kelstadt and Prima Vista Bridges (the preferred location of the low salinity zone). The volume of water needed to place the 1 psu isohaline between these two locations was identified as a series of pulsed flows delivered from the Gordy Road Structure that equate to a mean monthly flow of 130 cfs (**Figure 8.1**). This quantity of water represents the flow target for the North Fork of the St. Lucie River. Both the performance measure and hydrologic target relate to maintaining the low salinity zone as a critical habitat for juvenile and larval fish during the dry season within the North Fork of the St. Lucie River

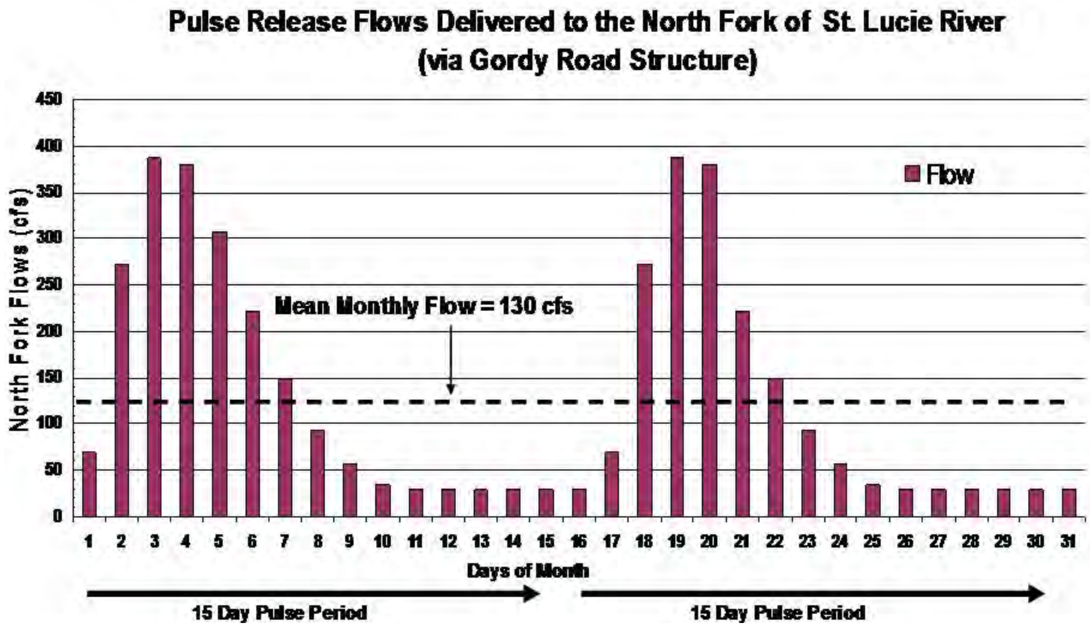

Figure 8.1. Pulse release schedule for the North Fork of the St. Lucie River.

Figure 8.1 provides an illustration of the District's concept for the delivery of pulse release flows from the project reservoir downstream to the Gordy Road Structure and the North Fork of the St. Lucie River. On Days 1-3, the Gordy Road Structure discharges rapidly increase to about 385 cfs. As discussed in **Section 7**, these initial pulse releases generally move the freshwater/saltwater interface (1 psu isohaline) and associated estuarine turbidity maximum downstream to the Kelstadt Bridge located at river mile 17.2. As flows gradually decline from Days 4 to 15, the location of the 1 psu isohaline (low salinity zone) gradually recedes upstream to the Prima Vista Bridge (river mile 23.1). As this process occurs, suspended sediments, bacteria, and particulate organic material are physically trapped within the estuarine turbidity maximum, providing a food source for larval and juvenile fishes. A short distance downstream from the 1 psu isohaline, phytoplankton growth occurs (the chlorophyll *a* maximum), which provide a food source for zooplankton that become prey for larval and juvenile fishes (**Section 6**). These pulse releases are repeated twice over a 30-day period. This pulsed flow regime represents a mean monthly flow of about 130 cfs, which equates to approximately 7,993 acre-feet of water delivered to the North Fork over the 30-day period.

Mean monthly flows within the range of 130 cfs represent the optimum flow regime needed to maintain the low salinity zone between the Prima Vista Bridge and Kelstadt Bridge locations. Therefore, a mean monthly flow of 130 cfs represents the proposed flow target that defines the volume of fresh water needed to be delivered by the Ten Mile Creek Basin (Gordy Road Structure) during the dry season to protect larval and juvenile fish habitat within the North Fork of the St. Lucie River.

8.2 Volume Probability Curves

To identify the quantity of water needed to protect fish and wildlife, volume probability curves were used to depict the distribution of water provided to the natural system as a result of implementing the Indian River Lagoon – South Project features through the entire range of climatic conditions simulated by the hydrologic model (1965 through 2005), or for different time windows (e.g., wet and dry seasons). These volumes of water include water that currently exists without project features and water made available by the project through the entire simulation period. Volume probability curves depict the range of water quantities delivered from the watershed to the North Fork of the St. Lucie River under a wide range of climatic conditions simulated by the WaSh/OPTI-6 models (**Figure 8.2**). These data can also be aggregated to represent different timing windows such as the wet season (June 1 to October 31) and the dry season (November 1 to May 31), as shown in **Figures 8.3** and **8.4**. This 41-year simulation period provides sufficient climate variability, including natural rainfall and flow variations representative of long-term hydrologic conditions within the watershed.

The daily time series of flow produced by the WaSh and OPTI-6 models were converted to mean monthly flow values for the 2050 Future with Project Condition and 2050 Future without Project Condition to match the North Fork flow target. Mean monthly flow data are expressed as a flow rate (cfs) and also in terms of volume (acre-feet) as shown in **Figures 8.2**, **8.3**, and **8.4**. Using the 2050 Future without Project Condition and 2050 Future with Project Condition data sets, the mean monthly flow data was sorted for volume and rank and compared against the North Fork flow target The volume probability curves rank the mean monthly surface flows from the lowest to the highest value using the Cunnane (1978) plotting position method: $p_i = (i-0.4)/(n+0.2)$. The smallest data value is assigned a rank of $i=1$, while the largest value receives a rank $i=n$, where n is the sample size of the data set. For instance, a dry season spans a duration of seven months from November 1 to May 31; with 41-years of data beginning January 1, 1965, the sample size equals 287.

The ranked flow series are then plotted as volume probability curves for each simulation period: (A) the entire 41-year simulation period (**Figure 8.2**), (B) the wet season (**Figure 8.3**), and (C) the dry season (**Figure 8.4**). On each graph the following traces are shown: (1) mean monthly flows delivered for the 2050 Future without Project Condition, (2) mean monthly flows delivered from the 2050 Future with Project Condition, and (3) the North Fork flow target (130 cfs). The volume probability curves provided in **Figure 8.4** serve as the basis for quantifying water for the protection of fish and wildlife in the North Fork.

8.3 Quantification of Water for the North Fork

Figures 8.2, **8.3**, and **8.4** compare the volumes of surface inflow delivered to the North Fork via Ten Mile Creek Basin (Gordy Road Structure) for the 2050 Future without Project and 2050 Future with Project Conditions for the 1965 through 2005 simulation period. These two model simulations were then compared to the North Fork flow target. The 2050 Future without Project Condition is only shown for comparative purposes. Since development of the flow target was based on the dry season when larval and juvenile fish are most sensitive to changes in freshwater inflows, a wet season flow target was not developed.

Review of **Figure 8.4** shows that under the 2050 Future without Project Condition (dashed black line), the proposed flow target (solid blue line) is only met about 9 percent of the time. In contrast, under the 2050 Future with Project Condition (dashed red line) the flow target is met more than 90 percent of the time (about 9 out of 10 years). Occasional low rainfall conditions within the watershed mean the target could not be met at about a 1-in-10 year frequency, which is consistent with the historical rainfall record presented in **Section 4.3** of this report.

Further analysis of these data showed that the sources of flows at the Gordy Road Structure originate primarily (~90%) from the C-23/C-24 Reservoirs and Stormwater Treatment Area. These waters are diverted from the C-23 and C-24 Canals into the project components and then discharged to Ten Mile Creek to flow over the Gordy Road Structure (**Figure 8.5**).

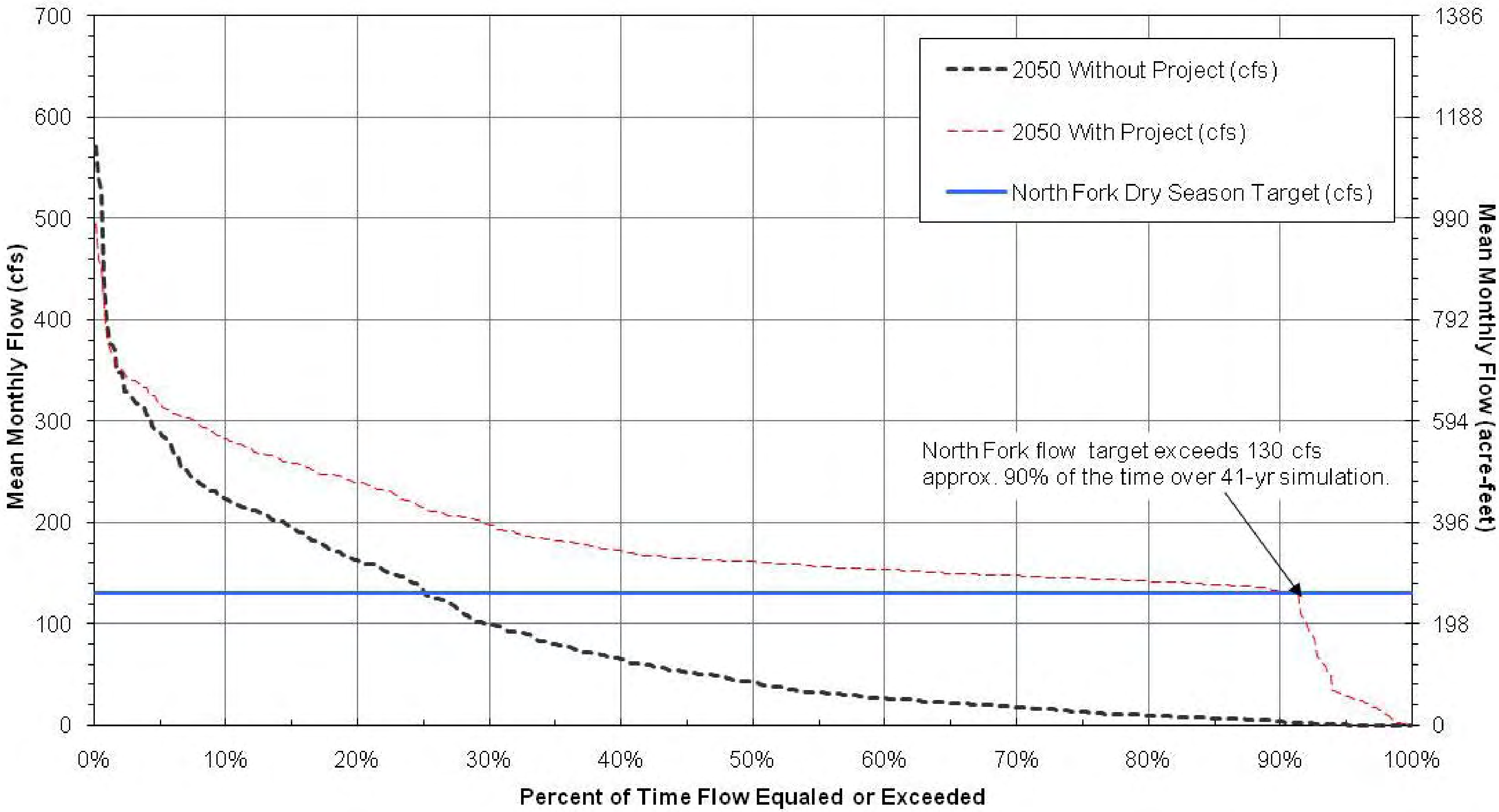

Figure 8.2. Volume probability curve for surface water deliveries into the North Fork at Gordy Road for 2050 Future with Project Condition, Future without Project Condition, and North Fork flow target for the 41-year period of record (1965–2005).

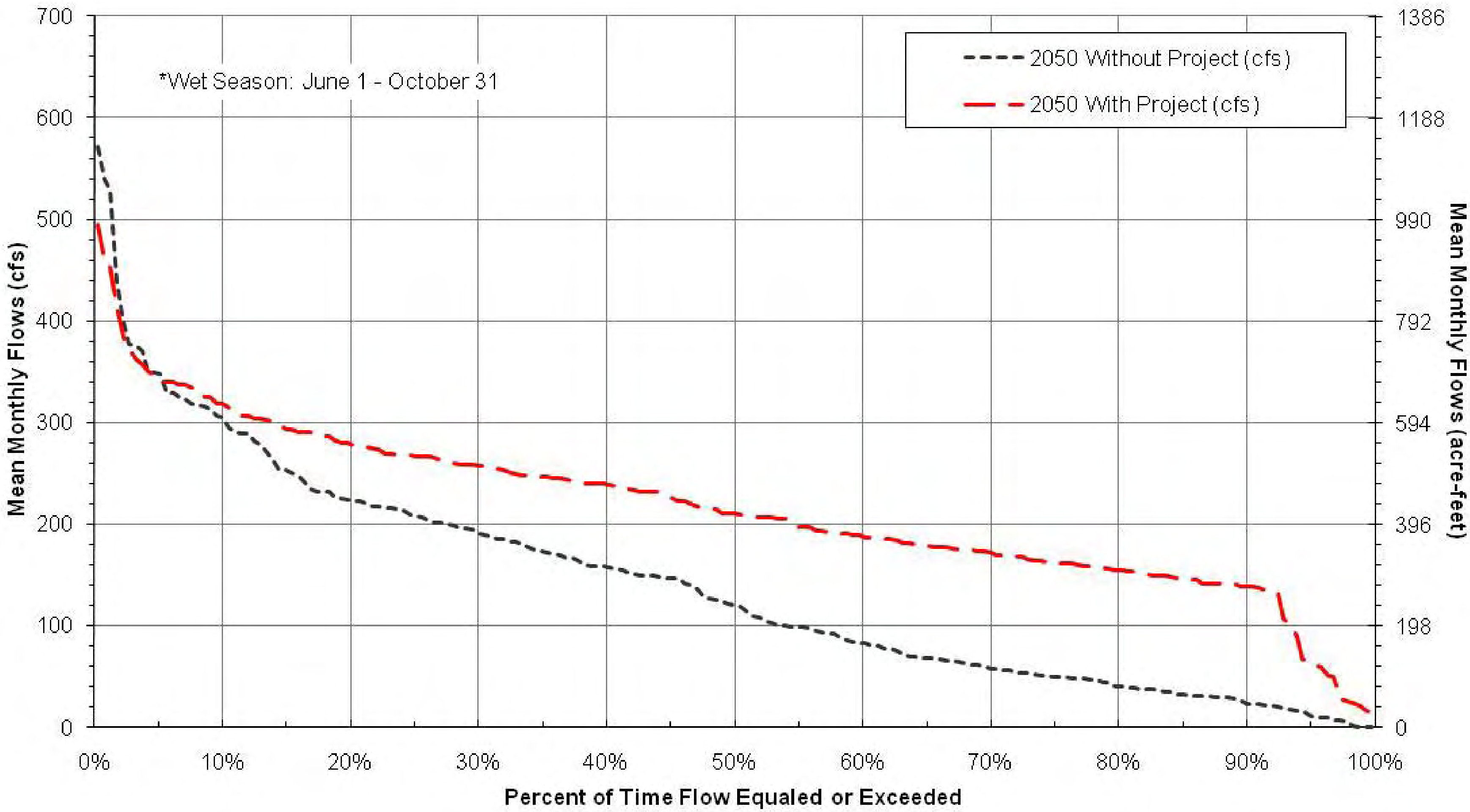

Figure 8.3. Volume probability curve for surface water deliveries into the North Fork at Gordy Road for wet seasons during the 41-year period of record (1965–2005).

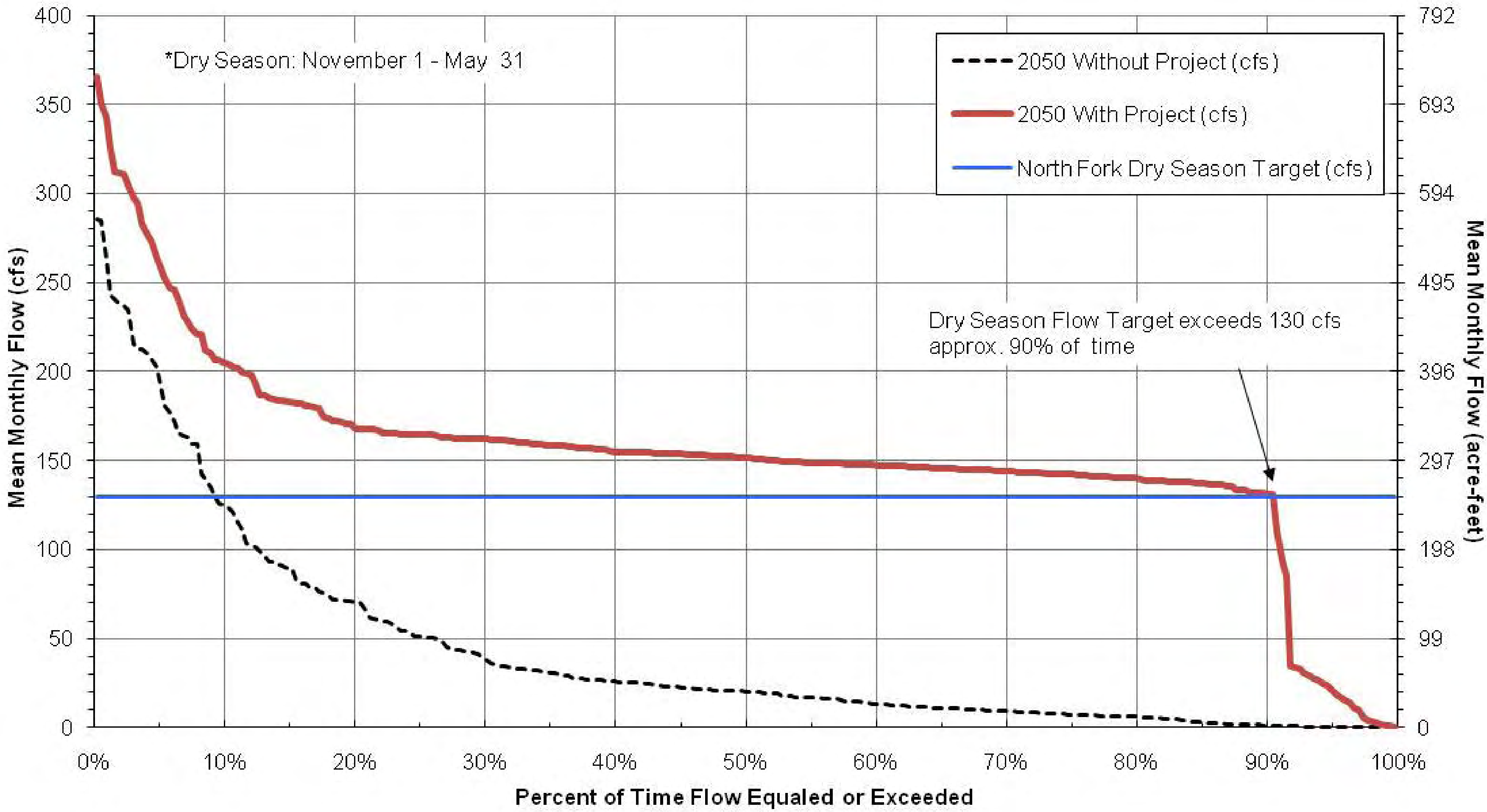

Figure 8.4. Volume probability curve for surface water deliveries into the North Fork at Gordy Road for dry seasons during the 41-year period of record (1965–2005).

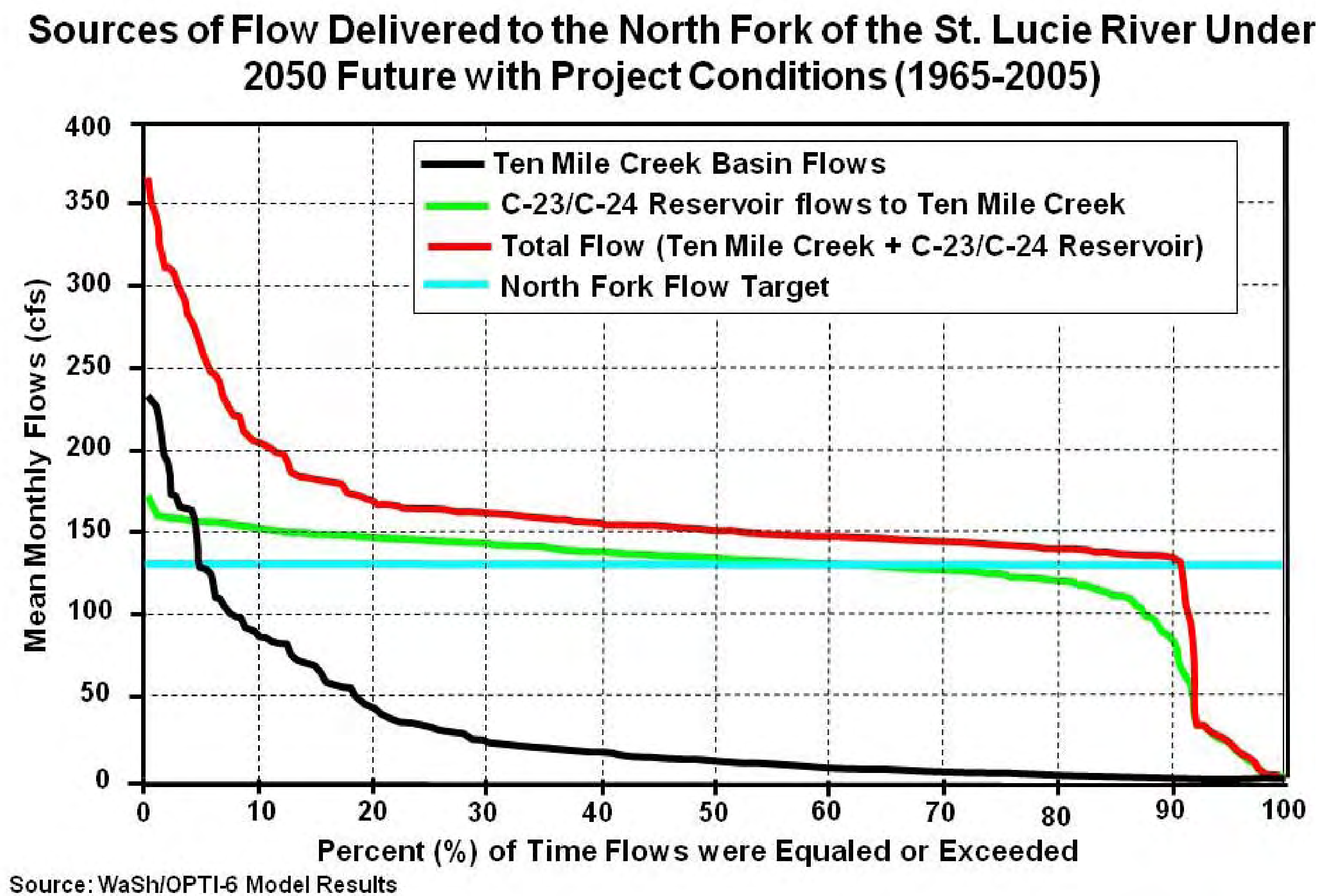

Figure 8.5. Sources of water contributing to flows at the Gordy Road Structure during the dry season.

Section 9. Water to Be Reserved for Protection of Fish and Wildlife

The identification of existing water and water produced by the project is based on that portion of water that is considered beneficial for the protection of fish and wildlife. The 2050 Future with Project Condition model simulation identified a quantity of additional water in the project reservoirs that could be used to benefit larval and juvenile fishes within the North Fork of the St. Lucie River to meet the goals and objectives of the Indian River Lagoon – South Project. This defined quantity of water that has been identified as beneficial to the natural system is the subject of the proposed water reservation.

The overall strategy is to reserve water in the dry season (November 1–May 31) when flows to the North Fork of the St. Lucie River tend to be the most critical for protection of fish and wildlife. The reservation in the North Fork is based on the mean monthly flow target of 130 cfs. Data applied in the volume probability curves for the water reservation was based on the quantification process described in **Section 8**.

In general, the volume of water shown beneath the flow target shown in the volume probability curve (**Figures 8.4** and **9.1**) represents the volume of water to be reserved under the proposed rule to protect fish and wildlife. If the water made available by the Indian River Lagoon – South Project (2050 with Project Condition) does not meet the target, then all water less than the target shall be reserved.

9.1 North Fork Flow Target

Based on the modeling results presented in **Section 7**, a mean monthly flow of approximately 130 cfs represents the target amount of fresh water needed to be delivered from the Ten Mile Creek Basin (Gordy Road Structure) during the dry season to protect larval and juvenile fish habitat within the North Fork of the St. Lucie River. The SFWMD has determined this quantity of water will result in the protection of fish and wildlife.

The flow at the Gordy Road Structure originates primarily from the C-23/C-24 Reservoirs and Stormwater Treatment Area, which is diverted from the C-23 and C-24 Canals into the project components and then discharged to Ten Mile Creek to flow over the Gordy Road Structure. The flow at the Gordy Road Structure for the 2050 Future with Project Condition is compared to the North Fork flow target (**Figure 8.4**). The reservation can be identified as the portion of the available water delivered by the 2050 Future with Project Condition up to, but not exceeding, the North Fork target flow. The target is equal to the 2050 Future with Project Condition during the wet season and will not be subject to protection via the water reservation rule. The volume of water shown on **Figure 9.1** is identified as the quantity of needed for the protection of fish and wildlife and will be reserved under state rule. The target is met approximately 90 percent of the time in the dry season. There is minimal water flow (< 40 cfs) available the remaining 10 percent of the time to meet the North Fork flow target.

9.2 Periodic Update of Technical Document and Rule

The scientific and technical information that identified the North Fork flow target, as well as the water reservation rule based on it, will be periodically reviewed and updated. As new information becomes available, the scientific and technical underpinnings of the linkages between hydrology and the ecological response will be revisited. Ideally, additional data will solidify the relationship among the location of the low salinity zone, estuarine turbidity maximum, total suspended solids, chlorophyll *a* maximum, and the ecological response of larval and juvenile fish within the North Fork of the St. Lucie River. This data collection will occur prior to and after construction of the C-23/C-24 Reservoirs and Stormwater Treatment Area to compare natural pulsed events to managed events. Once the C-23/C-24 construction project is complete, it will enter an operational testing phase where the principles of adaptive management and analysis resulting from previously collected data will be applied to fine tune the operations. In addition, FDEP rule 62-40.474, F.A.C. provides guidance to anticipate how the rule will be adjusted if the actual water made available differs from the quantities anticipated.

When the South Florida Water Management District Governing Board determines the C-23/C-24 Reservoirs and Stormwater Treatment Area are operational and if the actual flow differs from the reserved volumes, then the Governing Board can initiate rule development to adjust the reservation. At that time or earlier, the Governing Board will also initiate rule development to regulate allocation of water from the CERP project. It is anticipated under certain conditions that water made available by the project may exceed the quantity needed for the protection of fish and wildlife. This quantity of water that is not identified for the protection of fish and wildlife and will not be reserved by the state may be considered for other water-related needs in the region at this time. However, should a determination be made that all or a portion of this water is necessary for restoration of the natural system at a future date, the state shall take appropriate actions to protect this water.

In the event that the C-23/C-24 Reservoirs and Stormwater Treatment Area are not constructed and determined to be operational by the SFWMD Governing Board, no additional rule development would be necessary to regulate the allocation of water provided by the project.

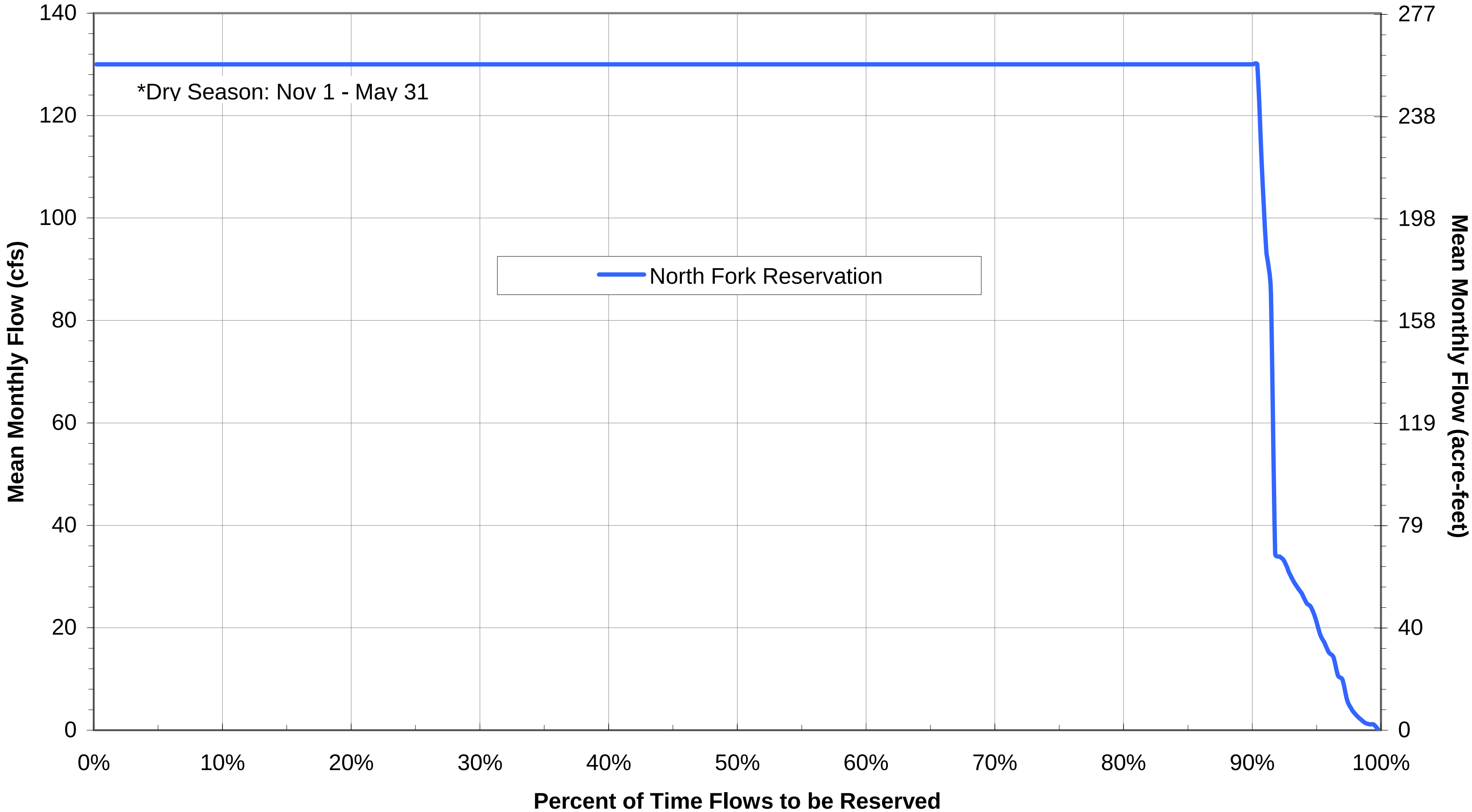

Figure 9.1. Volume probability curve of surface water deliveries into the North Fork at the Gordy Road Structure to be reserved for the dry season.

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Appendix A-1.
Report of the Peer Review Panel for the Draft Report, Technical Document to Support a Water Reservation Rule for the North Fork of the St. Lucie River

Note: Other than minor formatting, this document has not been changed from what was submitted by the Peer Review Panel.

Report of the Peer Review Panel for the Draft Report,

Technical Document to Support a Water Reservation Rule for the

North Fork of the St. Lucie River

Submitted to the
South Florida Water Management District
West Palm Beach, Florida

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June 19, 2009

Contents

Executive Summary

1. This report of the Peer Review Panel addresses the scientific merit of a draft report by staff of the South Florida Water Management District (May 2009), concerning the technical basis for proposing a water reservation rule for the North Fork of the St. Lucie River, a coastal watershed that contributes to the greater Indian River Lagoon system of southeastern Florida.
2. The Peer Review Panel of four persons represents scientific expertise concerning physical aspects of surface and ground water, hydrologic and hydrodynamic modeling, biology of invertebrates and fishes, ecological structure and function of coastal ecosystems, and monitoring performance of resource management toward achieving environmental goals and objectives.
3. The draft report generally succeeds in attaining its goal to document technically the basis for reliably determining water flow patterns in the North Fork of the St. Lucie River, through an approach that overall is scientifically valid and uses currently accepted scientific practices and concepts.
4. One issue of special concern is the need to formulate in the report a plan for evaluation of how the water reservation performs, both physically and biologically, in terms of meeting ecological goals and objectives (stated in ways so that success in their attainment can be measured objectively and quantitatively) to protect fish and wildlife, particularly for periods when the region experiences dry or drought conditions.
5. The project approach of considering the physical conditions for habitat restoration as the first step in ecosystem recovery is in line with the valued ecosystem component approach and habitat overlap concept employed in the report.
6. The focus on salinity as a surrogate for estuarine ecosystem health is an acceptable way of assessing what freshwater flows are needed to sustain estuarine organisms that utilize low salinity areas.
7. Designation of a Low Salinity Zone as a key habitat is a suitable basis for guiding levels of freshwater required in the system to sustain plankton, invertebrate, fish and other living resources. The focus on freshwater flow to keep the oligohaline zone within a region of the North Fork of the St. Lucie River between the Prima Vista and Kelstadt bridges should provide a good start for recovery of key faunal elements.
8. The decision to use a salinity of 1 psu (i.e., "practical salinity unit") as a target metric for assessing system restoration is reinforced by a large literature on the importance of low salinity zones to estuarine productivity. Data from the St. Lucie system for benthos and fish eggs and larvae are sparse and need to be augmented early in the water reservation project.
9. The project design of two cycles of the 1-psu isohaline and associated turbidity maximum per month to enhance habitat for key species is based on sound ecological data and principles. Pulse flows of freshwater are a more natural condition for the North Fork, St. Lucie River.
10. The Estuarine Turbidity Maximum is a key factor to the biological aspects of the report. Its discussion in words and illustrations should be expanded to better demonstrate the relationship between salinity, total suspended solids, and chlorophyll *a* levels in the water column of the estuary. (Data from DYHYDRO, for example, could be used to produce longitudinal profiles of salinity and total suspended solids in the St. Lucie Estuary.)
11. Knowing when key resource species spawn and recruit to the North Fork, St. Lucie River will be central to the ecological success of the project. Preferred salinity ranges, habitat

use by life stage, period of the year present within the system, and ecological importance need to be described in the report, with gaps in data determined in near-term research.

12. The hydrologic and hydrodynamic models developed for the North Fork of the St. Lucie River and its watershed are deemed appropriate for this application. However, technical issues that need to be addressed prior to completing the final report include: Open boundary salinity conditions for hydrodynamic model predictions, spatial salinity profiles, calculated vs. measured salinity at Prima Vista Bridge and Midway, temporal plots of freshwater input to the St. Lucie Estuary, and vertical averaging of salinity results.
13. The percent of time that water required to meet the 130 cfs target discharge for the protection of fish and wildlife will be available is quantified in sections 8 and 9 of the draft report, based on the discharge values simulated using WaSh and OPTI-6 models. In general, these two sections need to be expanded to the same level of detail and explanation provided in Sections 1-7. Various methods, explanations, and suggested additional calculations should be added.
14. The 90.5% exceedance that the target discharge can be met during the dry season each year implies that there is approximately a 1 in 10 chance that the target flow cannot be met. What is the implication of this result, i.e., are there established standards of reliability for water resource projects such as this to which this result can be compared? Also, a more rigorous analysis of the simulated low flows should be carried out to improve the accuracy of the prediction for the percent of time (91.5%) that the target discharge of 130 cfs will be met. Within the adaptive management plan, special consideration needs to be given to how flow pulsing would be handled and how the ecosystem responds (see point 4, above).
15. In view of the recognition that inland terrestrial sources to coastal aquifers cannot sustain the magnitude of measured groundwater discharge and thus that some part of the measured discharge must originate from recirculated seawater, several important questions concerning the quality and quantity of the submarine groundwater discharge that was input as a boundary condition to the CH3D model need to be answered, concerning assumptions and sensitivity of the model and conclusions of the report.
16. It is recommended that the uncertainty concerning the impact of not including the Floridan aquifer in the WaSh model be assessed in the final technical report by comparing the estimated vertical leakage from the Floridan aquifer to the surficial aquifer system in this basin to the other water-budget components in the basin. Further, it is recommended that simulated groundwater heads in the WaSh model be compared with groundwater levels from selected wells in the basin as part of a long-term monitoring plan to determine how well the groundwater component in the surficial aquifer is represented in the WaSh model.
17. It is acknowledged in the draft report that model uncertainty associated with the reservoir optimization model OPTI-6 is extremely small as long as input data are correct, but that real-time day-to-day operation of the reservoir and water control structures may not be able to achieve the optimal results produced by OPTI-6. Therefore, it is recommended that discussion of this issue be expanded to include some indication of how reliable the simulations are considered to be.
18. The report conclusions need to include the hydrological details and predicted ecological benefits of flow pulsing, for example in synthesis of information on life-stages, salinity tolerance, time of year in the system and habitat needs of species.
19. In order to better understand and manage freshwater flow within this system, data on naturally occurring pulsed events need to be collected to determine how the system will respond both physically (includes hydrography and salinity) and biologically (includes

benthic and planktonic compartments). This information would feed into developing an adaptive management strategy for executing the pulsed flow regime.

20. A major part of the monitoring plan needs to be devoted to justifying the performance measures that will be used for assessing ecosystem response of both the benthic and pelagic components of the ecosystem. In the future, models of the biological energy flow through the North Fork, St. Lucie River should be developed as a means of assessing the ecosystem response to the project and also for assessing long-term change within the St. Lucie system.
21. An analysis of the existing water quality and zooplankton data in the St. Lucie River Estuary is missing from the draft report, and should be added in the final report.
22. While the draft technical document contains the elements of the project conclusions, they are not succinctly stated or in one central location. It would be helpful for the conclusions in different sections of the report to be gathered in one place, perhaps summarized in the executive summary.
23. The connectivity of the North Fork of the St. Lucie River to the greater regional ecosystem and broader plans for restoration needs an explicit description. Similarly, the connection of the report and its principles, concepts and assertions with the broader scientific knowledge base can be enhanced by additional reference and discussion of technical literature, with almost 50 citations for reference indicated in several places in the full report of the Peer Review Panel.
24. Staff from the Coastal Ecosystems, Everglades Restoration, Water Supply Planning, and Counsel offices of the District are commended for their collegial, sincere and innovative efforts to prepare a well written draft report plus an organized workshop and field site visit, and informative presentations that addressed some of the Panel concerns provided in written comments ahead of the June 1-3 workshop.

Introduction and Approach

This report addresses the scientific merit of a May 2009 draft report by staff of the South Florida Water Management District, concerning the technical basis for proposing a water reservation rule for the North Fork of the St. Lucie River, a watershed that contributes to the overall Indian River Lagoon of southeastern Florida, mainly in Martin and St. Lucie Counties. The technical document of just over 100 pages of narrative text, plus appendices, characterizes freshwater use and flow patterns in the 780-suare mile watershed of the North Fork of the St. Lucie River, and integrates biological and physical knowledge into a plan for establishing a water reservation that will sustain fish and wildlife resources in the estuarine ecosystem. A large amount of technical information was assembled. From a biological perspective, a central point of the staff analysis is the importance of maintaining a "low salinity zone" and associated phenomena in the ecosystem to sustain plankton, fishes and other aquatic resources. In turn, this integrates with hydrologic and hydrodynamic analyses and models for managing water storage and flow patterns and levels. (Complete details for the project are given at the District website.)

The Peer Review Panel of four persons represents collective, water-related scientific experience of many decades, and was constituted by the District for complementary individual expertise concerning physical aspects of surface and groundwater composition and flow, hydrodynamic and hydrologic modeling, biology of invertebrates and fishes, basic ecological structure and function as well as practical restoration of coastal ecosystems, statistical analysis of datasets, evaluation of natural resource-related research, and monitoring performance of water inflow management toward achieving environmental goals and objectives. Guiding concerns for this review are the degree to which the technical document achieves its stated objectives, the extent to which its approach and conclusions are scientifically valid, and the means whereby performance of its recommendations are to be evaluated.

The review began with review panelists reading the technical document and posting questions and requests for more information on the District web board topic for the "St. Lucie Estuary," in advance of a workshop held June 1-3, 2009 (agenda posted on web board). On-site, panelists extensively toured upland water reservation, flow and control locations in the watershed and also a long segment of the river, natural and canalized tributaries, and estuary, then heard staff presentations on all technical aspects of the proposed water reservation plan, and finally met to review both the technical document and the new information provided during the site visit. Panel deliberations were guided by attention to the eight principal questions posed by District staff at the start of the review in May, and which are used to organize the major part of this report.

The Peer Review Panel extends sincere thanks to staff from the Coastal Ecosystems, Everglades Restoration, Water Supply Planning, and Counsel offices for their collegial and sincere efforts, not only for a well-organized workshop and very helpful presentations that augmented the technical document, but also for ably and professionally representing the District to the diverse scientific and public sectors that share District concerns and goals for sustainability of aquatic habitats and ecosystems.

Findings and Recommendations of the Peer Review Panel

The format for this section, the heart of the Peer Review Panel report, is to provide comments about the technical accuracy and completeness of the " Draft Report, Technical Document to Support a Water Reservation Rule for the North Fork of the St. Lucie River," and make recommendations for additions and other revisions. These comments are based on both the original document made available before the workshop, and also the oral presentations at the workshop. Although some panel concerns may have been addressed and resolved at the workshop, some comments below still may be framed with reference to the paper document as a means of guiding collection and placement in the final District report of information gathered by staff after receipt of individual panel member written reviews, since that document, once revised, will be the benchmark and definitive source for the project.

Overall Comments

The report generally succeeds in attaining its goal to document technically the basis for reliably determining water flow patterns in the North Fork of the St. Lucie River, and is well written and logically organized. It deals with a complex subject that involves different biological and physical scientific subjects, made more complicated by a context of public policy and natural resources management seeking to apply the science effectively to achieve social and environmental goals. The deep knowledge and experience of District staff concerning this subject is apparent, as evidenced by use of currently accepted scientific practices and concepts.

The report, as a draft, also addresses certain topics incompletely, and easily could augment various sections with additional discussion of methods or reference to significant publications, for example. A simple guideline for revision should be the consideration of a reader who may lack day-to-day familiarity with the complex upland and aquatic ecosystem, the scientific concepts incorporated, and the technical methods employed, and also, more importantly, whether or not an informed "peer" could come to similar conclusions based on the information in the report. Because significant new information was provided in staff presentations (uniformly excellent) at the workshop, many revisions to the draft should be easy; this will make the document more rigorous.

One issue of special concern is the need to formulate a plan for evaluation of how the water reservation performs, both physically and biologically, in terms of meeting ecological goals and objectives that are listed in the technical document. As part of the overview, is it not appropriate to define the important terms of "recovery" and "ecological values"? From what condition will the system recover? And, what will be its condition when it is recovered? For each value in Table 3.1, how will attainment of them as part of the goals and objectives be measured? What does "improve" mean, and when do we know, quantitatively, that we have been successful?

Question1. Does the compiled information, including data, modeling and literature, provide an adequate technical basis for the conclusions reached?

Yes, the technical basis for the conclusions reached is "adequate," and represents a strong multi-disciplinary effort to apply best practices of physical and biological science. Yet--with a reasonable level of additional effort, using in part information already assembled for the workshop--it can be further developed to make it exceptionally rigorous and able to withstand close scrutiny. As indicated in following sections of this report (and also in advance written comments sent by panelists in May), there are a number of places where the report can be made more quantitative and informative. Specific issues are addressed under subsequent questions.

Secondly, while the draft Technical Document to Support a Water Reservation Rule for the North Fork of the St. Lucie River contains the elements of the project conclusions, they are not succinctly stated or in one central location. It would be helpful for the conclusions to be summarized in the executive summary.

A third general recommendation is that an explicit strategy for evaluating both hydrological and biological performance of the water reservation plan be presented in the technical document. Here, quantitative measures of success in reaching project goals and objectives should be specified.

Findings, recommendations and references concerning "compiled information":

While the watershed and hydrodynamic modeling effort is considered adequate for this study, additional details should be provided to enhance the technical basis for the report. Our comments and response to Question #4 offer significant insights into the technical issues with the hydrodynamic modeling effort when used in predicting the salinity levels in the estuarine system, i.e. the open boundary issue. Additional clarification is needed to explain the discrepancies between model calculated and measured salinity in the upper estuary where the estuarine turbidity maximum (ETM) is located.

The existing water quality conditions of the St. Lucie River Estuary are not fully documented in the report. We therefore recommend a more quantitative view of the existing water quality conditions by analyzing available data from DYHYDRO, assessing from currently available references and published reports (see our response to Question #5).

The report conclusions need to include the hydrological details and predicted ecological benefits of flow pulsing. For example, improved trophic value for the early life-stages of key resource species (North et al. 2005, North and Houde 2003) is expected and associated with the projected movement of the estuarine turbidity maximum between the Prima Vista and Kelstadt bridges. This trophic value will accrue from the enhanced secondary production of invertebrates (benthic and planktonic) associated with low salinity estuarine turbidity maximum zones (Diaz and Schaffner 1990, Yozzo and Diaz 1999). Which key estuarine species use this habitat need to be listed in a table along with information on life-stages, salinity tolerance, and time of year in the St. Lucie system, along with their habitat needs. (Also see guidance in Question 8 section of this document.)

Pulse flows of freshwater are a more natural condition for the North Fork, St. Lucie River. The project design of two cycles of the 1 psu isohaline and associated turbidity maximum per month to enhance habitat for key species has sound ecological data and principles. Odum (1969) was one of the first to develop the relationship between ecosystem state, developmental stage or disturbance level, and energy flows. Odum's pulsed ecosystem concept was developed from a cross-section of habitat and appears to be a principle applicable to terrestrial, freshwater, and marine systems (Odum 1969, Odum et al. 1995). It is based on successional theory, which predicts that ecosystems that are frequently disturbed maintain high but simple energy flows by virtue of the life-history characteristics of species able to tolerate disturbance (see Table 1). In the case of the North Fork, St. Lucie River the disturbance would be the pulsed release of freshwater that would move the 1 psu isohaline between the Prima Vista and Kelstadt bridges. While the data from the St. Lucie system for benthos and fish eggs and larvae are sparse, there is a large literature on the importance of low salinity zones to estuarine productivity that backs up the decision to use a salinity of 1 psu as a target metric for assessing system restoration (see Diaz and Schaffner 1990) and that trophic interactions are the main pathways by which energy is moved through an ecosystem (Odum 1984). The panel agrees that some of this literature can be discussed in the report.

Table 1. A tabular model of ecological succession: trends to be expected in the development of ecosystems (from Odum 1969). Tidal freshwater and low salinity habitats fit into the category of developmental stages.

Ecosystem attributes	Developmental stages	Mature stages
Community energetics		
1. Gross production/community respiration (*P/R* ratio)	Greater or less than 1	Approaches 1
2. Gross production/standing crop biomass (*P/B* ratio)	High	Low
3. Biomass supported/unit energy flow (*B/E* ratio)	Low	High
4. Net community production (yield)	High	Low
5. Food chains	Linear, predominantly grazing	Weblike, predominantly detritus
Community structure		
6. Total organic matter	Small	Large
7. Inorganic nutrients	Extrabiotic	Intrabiotic
8. Species diversity—variety component	Low	High
9. Species diversity—equitability component	Low	High
10. Biochemical diversity	Low	High
11. Stratification and spatial heterogeneity (pattern diversity)	Poorly organized	Well-organized
Life history		
12. Niche specialization	Broad	Narrow
13. Size of organism	Small	Large
14. Life cycles	Short, simple	Long, complex
Nutrient cycling		
15. Mineral cycles	Open	Closed
16. Nutrient exchange rate, between organisms and environment	Rapid	Slow
17. Role of detritus in nutrient regeneration	Unimportant	Important
Selection pressure		
18. Growth form	For rapid growth ("*r*-selection")	For feedback control ("*K*-selection")
19. Production	Quantity	Quality
Overall homeostasis		
20. Internal symbiosis	Undeveloped	Developed
21. Nutrient conservation	Poor	Good
22. Stability (resistance to external perturbations)	Poor	Good
23. Entropy	High	Low
24. Information	Low	High

The following publications offer information that can be incorporated into the discussion of the report, concerning the comments provided above:

Diaz, R. J. and L. C. Schaffner. 1990. The functional role of estuarine benthos. Pp. 25-56. In: M. Haire and E.C. Krome (eds.). Perspectives on the Chesapeake Bay, 1990. Advances in estuarine sciences. Chesapeake Research Consortium, Gloucester Pt., Virginia. Rpt. No. CBP/TRS41/90

North, E. W. and E. D. Houde. 2003. Linking ETM physics, zooplankton prey, and fish early-life histories to striped bass *Morone saxatilis* and white perch *M. americana* recruitment. Mar. Ecol. Prog. Ser. 260:219-236.

North, E. W., R. R. Houde, S. Y. Chao, and L. P. Sanford. 2005. The influence of episodic events on transport of striped bass eggs to the estuarine turbidity maximum nursery area. Estuaries 28:108-123.

Odum, E. P. 1969. The strategy of ecosystem development. Science 164:262-270.

Odum, H. T. 1984. Systems ecology. John Wiley & Sons. New York.

Odum, W. E., E. P. Odum and H. T. Odum. 1995. Nature's pulsing paradigm. Estuaries and Coasts 37 18:547-555.

Yozzo, D. J. and R. J. Diaz. 1999. Tidal freshwater wetlands: invertebrate diversity, ecology, and functional significance. p. 889-918. In: D.P. Batzer, R.B. Rader and S.A. Wissinger (eds.), Invertebrates in Freshwater Wetlands of North America: Ecology and Management. John Wiley & Sons, New York.

Finally, additional, succinct explanation of the "connectivity" of both the report and the North Fork of the St. Lucie River to the larger body of scientific literature and available databases and also to the ecosystems of the region, respectively, would enhance the utility and strength of the draft report. This could be as simple as including selected maps from the workshop presentations, or a bit more involved (but still realistic) in terms of analysis and synthesis of additional technical knowledge, with specific topics noted below.

<u>Question 2. Is the Low Salinity Zone (LSZ) a suitable Valued Ecosystem Component (VEC) for defining freshwater flow requirements? Are there other environmental indicators that should have received further consideration as potential VECs?</u>

The focus on salinity as a surrogate for estuarine ecosystem health is an acceptable way of assessing what freshwater flows are needed to sustain estuarine organisms that utilize low salinity areas. This goes back to the beginnings of estuarine ecology when Remane (1934, 1971) determined that salinity was the major factor controlling biodiversity. Salinity is considered a key master factor for all aquatic organisms. The other master factors are temperature and dissolved oxygen (Hedgpeth 1957). The project approach views getting the physical conditions for habitat restoration as the first step in ecosystem recovery, which is in line with the valued ecosystem component approach and habitat overlap concept.

Tidal freshwater and low salinity areas tend to be characterized by variable low to high abundance and biomass with low to moderate species richness and diversity (Crumbs 1977, Diaz 1989, Diaz and Schaffner 1990, Dauer and Alden 1995, Strayer 2006). Table 2 lists the characteristics of tidal freshwater and oligohaline zones in Chesapeake Bay. There is a good deal of blurring of the fauna along the salinity gradient and it is common to find marine species well into tidal freshwater, but few freshwater species penetrate far into saline waters (Simpson et al. l985). These characteristics have made the development of indices and valued ecosystem components difficult and not successful for invertebrate communities (Weisberg et al. 1997).

Table 2. Characteristics of tidal freshwater and oligohaline benthic habitats in Chesapeake Bay (modified from Diaz and Schaffner 1990).

Habitat Type	Physical Characteristics	Macrobenthic Community Characteristics	Macrofauna Density	Macrofauna Biomass
Tidal Freshwater				
Shoals	**Shallow depths Mud to sand sediments Wave & tide dominated High turbidity & allochthonous carbon Low to moderate light penetration.**	**Stenohaline, otherwise eurytopic fauna Deposit and suspension feeders Moderate diversity**	**Low**	**Bivalves high Others low**
Channels	**Intermediate depths Mud to sand sediments Fluid mud possible Tide-dominated High turbidity & allochthonous carbon No light penetration**	**Stenohaline, otherwise eurytopic fauna Deposit and suspension feeders Moderate diversity**	**Low**	**Bivalves high Others low**
Oligohaline				
Shoals	**Shallow depths Mud to sand sediments Wave & tide dominated High deposition & allochthonous carbon Low to moderate light penetration**	**Euryhaline, eurytopic fauna Deposit and suspension feeders Low diversity**	**Low to high**	**Bivalves high Others low**
Channels	**Moderate depths Mud sediments Fluid mud possible Tide-dominated High deposition & allochthonous carbon No light penetration**	**Euryhaline, eurytopic fauna Deposit and suspension feeders Low diversity**	**Low to high**	**Bivalves high Others low**

One aspect of the report that can be strengthened is in its foundations upon the larger body of science from which it is drawing. For example, Section 6.1 lists five “valued ecosystem components” that were considered prior to selecting one, the low salinity zone (LSZ), for emphasis. The rationale for this choice is good. However, the text needs to state why the other components (e.g., submerged vegetation) were dropped from consideration. Indeed, a concise section of text (perhaps with a table) that synthesizes the comparison of the five components would be quite useful, and perhaps further strengthen the case for the LSZ. Further, what are the “available data” for both the low salinity zone and also the other components?. Likewise, are there peer-reviewed articles that evaluate the approach and results of the VEC method, which is based on a 1987 report? Is this method used only in South Florida? Actually, most references seem to come from other nations. The report states, “Both the valued ecosystem component approach and the habitat overlap concept have been used by District staff…" (p.6) in planning for the Loxahatchee River, Florida Bay and Caloosahatchee estuary. How has this approach worked? What evaluation has been made? The "habitat overlap concept" (pp. 6-1-6-2) is based on a reference published in 1981. Are there no scientific literature references to its use much more recently? (See other related recommendations below.) Some of the material contained in slides used at the workshop addresses this issue.

These publications are suggested for review and incorporation into the report text sections as a means of enhancing the discussion:

Crumbs, S. E. 1977. Macrobenthos of the tidal Delaware River between Trenton and Burlington, New Jersey. Chesapeake Science 18:253-265.

Dauer, D. M. and R. W. Alden, II. 1995. Long-term trends in the macrobenthos and water quality of the lower Chesapeake Bay (1985-1991). Marine Pollution Bulletin 30:840-850.

Diaz, R.J. 1989. Pollution and tidal benthic communities of the James River Estuary, Virginia. Hydrobiologia 180:195-211.

Diaz, R. J. and L. C. Schaffner. 1990. The functional role of estuarine benthos. Pp. 25-56. In: M. Haire and E.C. Krome (eds.). Perspectives on the Chesapeake Bay, 1990. Advances in estuarine sciences. Chesapeake Research Consortium, Gloucester Pt., Virginia. Rpt. No. CBP/TRS41/90

Hedgpeth J.W. (ed.). 1957. Treatise on Marine Ecology and Paleoecology, Volume 1, Baltimore: Waverly Press.

Remane, A. 1934. Die Brackwasserfauna. ZooL Anz. Suppl. 7: Verhandl. Deut. Zod. Ges. 36:34-74.

Remane, A. 1971. Ecology of brackish water. Die Binnengewasser 25:1-210.

Simpson, K. W, J. P. Fagnani, Denicola, D. M., and R. W. Bode. 1985. Widespread distribution of some estuarine crustaceans (*Cyathura polita, Chiridotea almyra, Alrmyracuma proximoculi*) in the limnetic zone of the lower Hudson River, New York. Estuaries 8:373-380.

Strayer, D. L. 2006. The benthic animal communities of the tidal-freshwater Hudson River Estuary. pp. 266-278. In: J. S. Levinton and J. R. Waldman (eds.). The Hudson River Estuary. New York: Cambridge University Press.

Weisberg, S. B., J. A. Ranasinghe, D. M. Dauer, L. C. Schaffner, R. J. Diaz and J. B. Frithsen. 1997. An estuarine benthic index of biotic integrity (B-IBI) for Chesapeake Bay. Estuaries 20:149-158.

<u>Question 3. Does the 1 ppt isohaline associated with the Estuarine Turbidity Maximum (ETM) provide a scientifically defensible performance measure for defining freshwater flow requirements?</u>

The 1-psu isohaline is an ecologically defensible performance measure for setting freshwater flows for restoring a low salinity habitat to enhance populations of key resource species. The ETM associated with the interface of freshwater and seawater is incidental. Salinity would be the only performance measure needed to define freshwater flows. But salinity and ETM are linked by the physics of estuarine circulation.

A 130 cfs mean monthly flow would move the estuarine turbidity maximum from the Prima Vista bridge to the Kelstadt bridge in five days and would take 10 days to return to the Prima Vista bridge area. Two cycles per months for April, May, and June are planned. The monitoring of this movement could be done entirely with salinity. The direct measurement of the estuarine turbidity maximum has gotten easier with the development of high resolution acoustic sensors and inexpensive sensors for suspended solids. But it is not necessary that turbidity or suspended solids be measured as the estuarine turbidity maximum can be inferred by measuring only salinity. As pointed out in the draft Technical Document to Support a Water Reservation Rule for the North Fork of the St. Lucie River, the location of the turbidity maximum is interconnected with suspended sediment concentrations, salinity, chlorophyll a, and planktonic organisms (see Figure 6.1 of the draft report).

Tidal freshwater areas are important to the productivity of estuaries in that they provide nursery grounds for many commercially important anadromous and catadromous fishes, such as shad, herring (alosids), striped bass *(Morone saxatilis)* and eels *(Anguilla rostrata*) (Massmann, 1954). They are the sites of large organic concentrations from river input and *in situ* production (Odum, *et al.,* 1984). All the major estuarine systems in North America have extensive tidal freshwater and low salinity systems, for example the Columbia River, San Francisco Bay, Hudson River, Delaware Bay, Chesapeake Bay, Pamlico Sound, Albemarle Sound, St. Johns, and St. Lawrence systems (Crumbs 1977, Odum et al. 1984, Diaz 1989, Diaz and Schaffner 1990, Jones et al. 1990, Weisberg et al. 1996, Kimmerer 2002). Similarly, major systems in Europe have extensive tidal freshwater and low salinity systems, for example Baltic Sea, and Ele River (Leppakoski 1975, Wolff 1972, Pfannkuche *et al.* 1975, Pfannkuche 1980, 1981).

Again, reference in the appropriate sections of report text to some or all of the following would add to the case being made:

Crumbs, S. E. 1977. Macrobenthos of the tidal Delaware River between Trenton and Burlington, New Jersey. Chesapeake Science 18:253-265.

Dauer, D. M. and R. W. Alden, II. 1995. Long-term trends in the macrobenthos and water quality of the Lower Chesapeake Bay (1985-1991). Marine Pollution Bulletin 30:840-850.

Jones, K. K., C. A. Simenstad, D. L. Higley and D. L. Bottom. 1990. Community structure, distribution, and standing stock of benthos, epibenthos, and plankton in the Columbia River Estuary. Progress in Oceanography 25:211-241.

Kimmerer, W. J. 2002. Physical, biological, and management responses to variable freshwater flow into the San Francisco estuary. Estuaries 25:1275-1290.

Leppakoski, E. 1975. Assessment of degree of pollution on the basis of macrozoobenthos in marine and brackish water environments. Acta Acad. Aboensis, Ser B 25:1-90.

Massmann, W. H. 1954. Marine fishes in fresh and brackish waters of Virginia rivers. Ecology 35:75-78.

Odum, W. E., T. J. Smith, III, J. K. Hoover and C. C. McIvor. 1984. The ecology of tidal freshwater marshes of the United States east coast: A community profile. U.S. Fish Wildl. Servo FWS/OBS-83/17. 177 pp.

Pfannkuche, O., H. Jelinek and E. Hartwig. 1975. Zur fauna eines susswasserwattes im Elbe-Aestuar. Arch. Hydrobiol 76: 475-498.

Pfannkuche, O. 1980. Distribution and abundance of Tubificidae and Naididae (Oligochaeta) in a brackish-water fjord, with special reference to the mesohaline zone. Netherlands J. Sea Res. 14:78-93.

Pfannkuche, O., 1981 Distribution, abundance and life cycles of aquatic Oligochaeta (Annelida) in a freshwater tidal flat of the Ele Estuary. Arch. Hydrobiol. Suppl. 43:506-524.

Weisberg, S. B., H. T. Wilson, P. Himchak, T. Baum, and R. Allen. 1996. Temporal trends in abundance of fish in the tidal Delaware River. Estuaries 19:723-729.

Finally, a minor point: Units for salinity have changed from ppt to psu (practical salinity unit). In the draft technical document, salinity areas are referred to as both oligohaline and low salinity. Oligohaline has a set definition with a salinity range of 0.5 to 5.0 psu. The term low salinity is defined in the draft technical document as 0 to 10 psu. In the Venice system that defines salinity zones, 0 to 10 psu would include freshwater (0 to 0.5 psu), oligohaline (0.5 to 5.0 psu), and part of the mesohaline zone (5.0 to 18.0 psu).

<u>Question 4. Are the hydrologic and hydrodynamic models appropriate for this application, and are they sufficiently supported by available knowledge, monitoring and research data (e.g., for calibration and validation) such that they yield credible evaluation results for this application?</u>

Three numerical models were used to simulate daily watershed inflows and salinity conditions for a 41-year period within the North Fork of the St. Lucie River for two conditions that represented the year 2050 with and without the project (p. 5-1 of the draft report). A hydrodynamics model (the Curvilinear Hydrodynamics Model [CH3D]) was used to simulate salinity conditions in the North Fork in response to pulse flow inputs at the upstream Gordy Road Structure (p. 5-2 and Figure 5.1). A hydrologic watershed model (WaSh) was used to simulate daily inflows from seven major basins that discharge surface water to the St. Lucie Estuary (p. 5-4). A reservoir optimization model (OPTI-6) was used to determine reservoir storage volumes that would reduce high volume freshwater discharges to the mid-estuary to protect oyster populations, to redistribute flows to the North Fork, and to maintain levels of service for flood protection and water supply (p. 5-4). While the hydrologic and hydrodynamic models developed for the St. Lucie River and its watershed are deemed appropriate for this application, there are a number of technical issues that need to be addressed prior to completing the final report.

Findings on Submarine Groundwater Discharge in the CH3D Hydrodynamic Modeling Effort

In this application of CH3D, groundwater inflow is recognized as submarine groundwater discharge (SGWD) across the entire estuary (p. 7-3), and it is an important boundary condition in CH3D. It was assumed that the salinity of the SGWD is zero (completely fresh) and that the volumetric inflow could be adjusted as a calibration parameter. A constant rate of 1.2 cm/day, which is equivalent to about 150 cfs for an estuary surface area of 11.3 square miles, was used in this application because that rate "…best matched the salinity gradient during the 2000 drought." (p. 7-26). This result is compared favorably with an average seepage rate of 1.3 cm/day measured in the St. Lucie River by Belanger et al. (2003) and an updated rate of 1.6 cm/day measured by Belanger et al. (2007). Also, the calibrated rate is considered "…very close to an early back-calculation [i.e., calibration adjustment] using a one-dimensional model by Morris (1987)." (p. 7-27).

In section 7.2.2, it is indicated that the CH3D model was used to simulate steady-state salinity conditions within a flow range of 30 cfs and 350 cfs at the Gordy Road Structure (p. 7-3). and that mean monthly flows of about 100 to 170 cfs "represent a range of potential target flows." (p. 7-4). Also, in Section 7.2.3, it is indicated that a mean monthly flow of 130 cfs is an appropriate target flow, because it "…has the ability to move the 1 ppt isohaline to the desired position." (p. 7-6). As a result, the groundwater inflow ("about 150 cfs", p. 7-26) in the CH3D boundary condition, which is assumed to have zero salinity, is of the same order of magnitude as the target freshwater inflow at the Gordy Road Structure (130 cfs mean monthly flow).

Recommendation on SGWD Boundary Conditions in CH3D

Measurements of SGWD, which consists of freshwater from inland terrestrial sources and re-circulated seawater that is due to such factors as wave setup and tides (Li et al. 1999), have been made in many parts of the world (e.g., Taniguchi et al. 2002). Generally, such measurements confirm the importance of re-circulated seawater (Motz and Sedighi 2009a and b). For example, based on field measurements in the Indian River Lagoon, Martin et al. (2007) estimated that the discharge of re-circulated seawater was more than two orders of magnitude larger than groundwater discharge from terrestrial sources. It has become recognized that inland terrestrial sources to coastal aquifers cannot sustain the magnitude of measured groundwater discharge and thus that some part of the measured discharge must originate from seawater (Moore and Church 1996). Accordingly, several important questions concerning the SGWD that was input as a boundary condition to CH3D need to be answered:

- How much does re-circulated seawater increase the salinity of what is measured as SGWD in the Indian River Lagoon?
- How do these results affect the assumption in the CH3D model that the salinity concentration in the groundwater inflow boundary condition is zero?
- Does this potentially change the results obtained from the CH3D model?
- How sensitive are the results for CH3D to the assumed salinity of the groundwater inflow (SGWD) in the estuary? Would it change the results and conclusions from the CH3D study (e.g., Figure 7-8, p. 7-20) if the salinity of the groundwater inflow, which is of the same order of magnitude as the target freshwater inflow at the Gordy Road Structure (130 cfs), were significantly greater than zero?
- Do the measurements of groundwater inflow and salinities made in the Indian River by Martin et al. (2007) affect the results and conclusions of the draft report?
- A recent study published as a conference proceedings (Yeh et al. 2009) presents the results of an investigation of groundwater seepage in the St. Lucie Estuary in which seepage measurements are compared to analytical model results. Do the results of this investigation affect the results and conclusions of the draft report?

Finding on Open Boundary Salinity Conditions for Hydrodynamic Model Predictions

Page D-17 of the draft report states that for boundary conditions, salinity is prescribed at ocean boundaries as a constant and equals 35 ppt when the tide is entering the model domain while an advection scheme is used to calculate salinity when the tide is leaving the model domain. It is not clear from the report what kind of advection scheme was used to derive the open boundary salinity boundary conditions during the ebb tide.

Further, assigning the open boundary salinity conditions in this fashion raises a concern in model predictions: What if the salinity levels at the open boundary are affected by the system response to freshwater pulses? If the salinity levels at the open boundary might be influenced by the estuarine salt content following certain flow change scenarios, they are not qualified as open boundary conditions. The following grid change for the 3-D Chesapeake Bay Hydrodynamic and Water Quality Model was needed simply to treat this problem and resolve this issue.

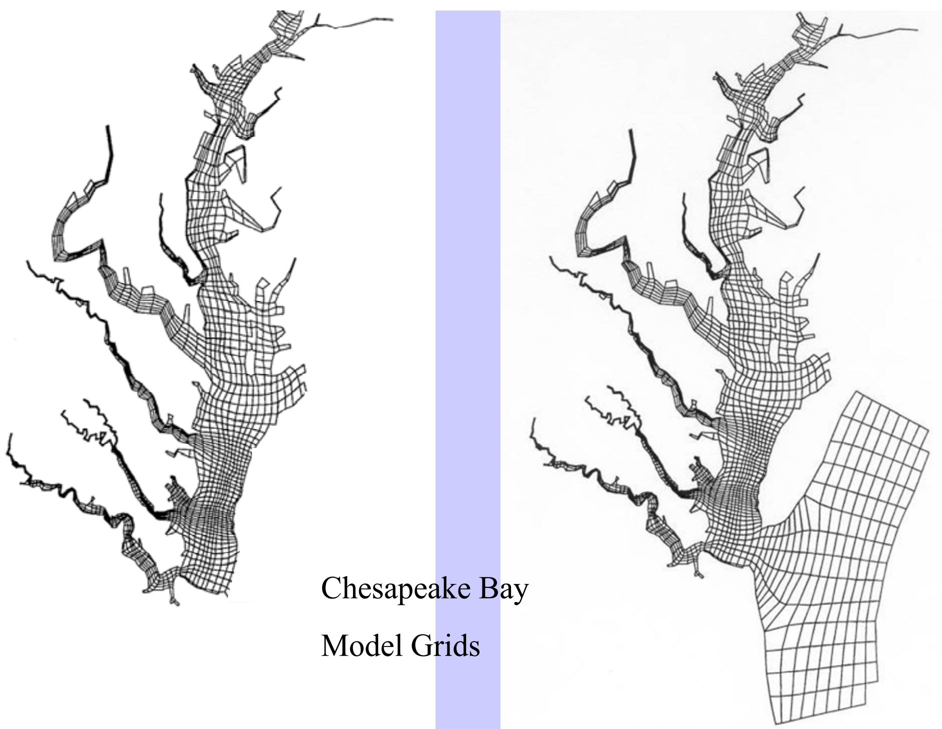


Figure 1. Chesapeake Bay model grids.

On the left is the original model grid of the Chesapeake Bay. The revised grid on the right eliminates the open boundary problem. That is, a constant salinity of 35 ppt is set at the open boundary of the new grid (with an expanded model domain) all the time

Recommendation on Open Boundary Conditions

The District technical staff should clarify the open boundary condition issue as discussed at the workshop to make sure that the open boundary of the St. Lucie River Estuary Hydrodynamic

Model is not affected by the system response in model predictions. Note that this issue is only germane to model predictions, not model calibration nor model verification.

Finding on Spatial Salinity Profiles

Temporal plots in Appendix D of the technical document can be supplemented with spatial salinity snapshots showing model results vs. field data to better demonstrate the interplay of spatial and temporal variations of salinity. The following figure (2) shows snapshots of salinity profiles in the Patuxent Estuary, Maryland (Lung and Nice 2007). These salinity plots clearly show the salinity intrusion tails as well as the portion of the river with salinity levels between 0 and 1 ppt. For the St. Lucie Estuary, such a region is critical to the biological habitat and is the key to this report.

Figure 2. Salinity profiles, Patuxent Estuary, Maryland.

Recommendation on Spatial Salinity Profiles

Plot snapshot spatial profiles of salinity in the St. Lucie Estuary (may consult the Patuxent Estuary work cited above).

Finding on Model Calibration and Verification

Note that the R^2 values for two locations, Prima Vista bridge and Midway (see Table 8, p. D-17), are low and much lower than those for the other stations in the table. It should be pointed out that salinity predictions at these two upstream locations are critical as the 1 ppt isohaline could easily take place between these two locations depending on the freshwater flow rates.

Recommendations on Model Calibration

The match between the model calculated salinity and measured data at Prima Vista Bridge and Kelstadt Bridge needs explanation. It is suggested that total freshwater input (in cfs) be added in Figures 10-15 to reflect the seasonal flow changes on the salinity levels in the estuary. Add the hydrograph of the freshwater input to the Estuary in Figures 10-15 of Appendix D. At Prima Vista, Midway, SE01 to SE04, HR1, SE06 to SE11, salinity is measured only at mid water column. How did you come up with model results (from 4 vertical layers) for comparison with data (Figures 12-15)? Also note that the comparison of model results and measured salinity at Station HR1 is not quite satisfactory. Is there an explanation? Vertical stratification is mentioned in p. D-4. Stratification of salinity, temperature, or dissolved oxygen at where? Surface and bottom salinity are measured at Kelstadt in 1999 and 2003. Are the data (shown in Figures 10 and 11 for comparison with model results) the average of the surface and bottom?

Findings on WaSh Model

The WaSh model is capable of simulating hydrologic conditions in watersheds with high groundwater tables and dense drainage canal networks, i.e., conditions that are typical in south Florida (p. C-5). The model was developed based on restructuring the Hydrologic Simulation Package FORTRAN (HSPF) into a cell-based system with the addition of a groundwater model and a full dynamic channel routing model (Wan et al. 2003). WaSh consists of four basic components, i.e., a cell-based representation of the watershed basin land surface, a groundwater component, a surface-water drainage system, and a water management component that can consider the effects of reservoirs, stormwater treatment areas, irrigation supply and demand, and land-use changes (p. C-6). The WaSh model was implemented in seven primary and three minor drainage basins (p. 7-13). Model inputs included primary and secondary basin boundary coverage, polygon features with basin name attributes, hydrography including streams and canals as line or polygon features, the 2000 base land use coverage, land surface elevations, rainfall, and evapotranspiration. Measured data collected at major flow structures and selected monitoring stations in the watershed were used for model calibration and validation.

Flow data from 1994 to 2000 were used for model calibration and from 1965 to 1993 for model validation (p. C-16). Two criteria were used to evaluate the calibration and validation performance of the WaSh model, i.e., the deviation of volume (DV), which quantifies the difference between observed and simulated water volumes, and the Nash-Sutcliffe coefficient, which measures how well the daily simulated flow corresponds with the measured flow (pp. C-17 and C-18). Based on these criteria, it is considered that the model simulated daily flows "reasonably well … for both C-23 and C-24 in the calibration period…[but] the performance during the validation period is not as good as [the] calibration [period]…." (Table C2-5 and p. C-18). Uncertainties in model representation, model parameters, and model input are considered to be sources of uncertainty and errors in the calibration and validation (p. 7-24). Uncertainties in the groundwater boundary condition in the WaSh model due to a lack of measured well stage data in the St. Lucie River watershed are considered to be a major source of model input uncertainty (p. 7-25).

Recommendations for WaSh Model

In Section 7.5.2 WaSh Model (p. 7-24 and 7-25), it is noted (p. 7-25) that "the groundwater boundary condition in WaSh is considered a major source of model input uncertainty…[d]ue to the lack of measured well stage data in the St. Lucie River watershed…." and "…that the Floridan aquifer is not included in the WaSh model."

- It is recommended that the uncertainty concerning the impact of not including the Floridan aquifer in the WaSh model be assessed by comparing the estimated vertical leakage from the Floridan aquifer to the surficial aquifer system in this basin to the other water-budget components in the basin (rainfall, evapotranspiration, surficial aquifer inflow and outflow, and surface-water inflow and outflow).

- In Appendix C2. Simulating Watershed Hydrology Using WaSh, it is indicated that the WaSh model has a groundwater component (Equation [C2-1], p. C-7) expressed in terms of groundwater elevation h. It is recommended that simulated groundwater heads in the WaSh model be compared with groundwater levels from selected wells in the basin to determine how well the groundwater component in the surficial aquifer is represented in the WaSh model.

Findings on OPTI-6 Model

The St. Lucie Reservoir Operation and Optimization Model (OPTI), which optimizes the size and operation of storage reservoirs and stormwater treatment areas, was updated for application in this water reservation (p. 5-6). The revised reservoir optimization model (called OPTI-6), which incorporates the option of off-line reservoirs along with fuzzy logic to produce operation rules (Wan et al. 2006), was used to represent the 2050 Future with Project Condition (p. 5-5). The model consists of a genetic algorithm module, a fuzzy logic module, and a drainage network simulation model (p. C-23). The flow time series simulated using WaSh was used as input to the OPTI-6 model to simulate freshwater flows delivered from the watershed under the 2050 Future with Project Condition. (p. 7-17). OPTI-6 was used to achieve the primary objectives of changing the stormwater flows into the SLE watershed to maintain Ten Mile Creek flow to North Fork at Gordy Road > 130 cfs, reduce months of low flow (< 350 cfs) and high flow (> 2,000 cfs) to SLE, and reduce the frequency of irrigation failure (p. C-32). A comparison of calculated monthly flows with target flows indicates that the monthly flow at Gordy Road was greater than 130 cfs during 91.5 % of the months during the 41-year simulation period and that the months of low flow (< 350 cfs) and high flow (> 2,000 cfs) were significantly reduced (p. C-32). Also, the optimization results indicated that irrigation requirements were met in all basins (p. C-32).

Recommendations for OPTI-6 Model

It is acknowledged that model uncertainty associated with OPTI-6 is extremely small as long as input data are correct, but that real-time day-to-day operation of the reservoir and water control structures may not be able to achieve the optimal results produced by OPTI-6 (p. 7-26).

- It is recommended that this discussion of the uncertainty associated with OPTI-6 be expanded to include some indication of how reliable the simulations are considered to be, i.e., how sensitive the simulations are to real-time day-to-day operation of the reservoir and water control structures, and the consequences of not achieving the optimal results produced by OPTI-6.

The following references are used in the above discussion and should be considered in revising the technical report:

Belanger, T. V., Heck, H. H., Gefvert, C., and Krupa, S. 2003. Seepage meter program for St. Lucie River and Indian River Lagoon. South Florida Water Management District. C-11835, West Palm Beach, Florida.

Belanger, T. V., Price, T. L., Jr., and Heck, H. H. 2007. Submarine groundwater discharge in the Indian River Lagoon, Florida: How important is it? Florida Scientist 70: 344-362.

Li, L., Barry, D. A., Stagnitti, F., and Parlange, J.-Y. 1999. Submarine groundwater discharge and associated chemical input to a coastal sea. Water Resources Research, 35(11):3253-3259.

Lung, W.S. and Nice, A.J., 2007. A eutrophication model for the Patuxent Estuary: Advances in predictive capabilities. *Journal of Environmental Engineering*, 133(9): 917-930, 2007.

Martin, J. B., Cable, J. E., Smith, C., Roy, M., and Cherrier, J. 2007. Magnitudes of submarine groundwater discharge from marine and terrestrial sources: Indian River Lagoon, Florida. Water Resources Research, vol. 43, W05440, doi:1029/ 2006WR005266.

Moore, W. S., and Church, T. S. 1996. Submarine groundwater discharge. Nature 382(6587):121-122.

Morris, F. 1987. Modeling of hydrodynamics and salinity in the St. Lucie Estuary. Technical Publication 87-1, South Florida Water Management District, West Palm Beach, Florida.

Motz, L. H., and Sedighi, A. 2009a. Analysis of saltwater intrusion and recirculation of seawater at a coastal boundary, American Society of Civil Engineers (ASCE) Environmental and Water Resources Institute and the Asian Institute of Technology (AIT), Bangkok, Thailand, January 5-7.

Motz, L. H., and Sedighi, A. 2009b. Representing the coastal boundary condition in regional groundwater flow models. Journal of Hydrologic Engineering, ASCE, vol. 14, no. 8, August.

Taniguchi, M., Burnett, W. C., Cable, J. E., and Turner, J. V. 2002. Investigation of submarine groundwater discharge. Hydrological Processes, 16(11):2115-2129.

Wan, Y., Reed, C., and Roza, E. 2003. Modeling watersheds with high groundwater tables and dense drainage canals. Proceedings of the 2003 AWRA International Conference: Watershed Management for Water Supply. June 29-July 2, p. 10.

Wan, Y., Labadie, K. D., Konyha, K. D., and Conboy, T. 2006. Optimization of frequency distribution of freshwater inflows for coastal ecosystem restoration. Journal of Water Resources Planning and Management, ASCE, 132:320-329.

Yeh, G.-T., Lee, J.-Y., Hu, G., and Sun, D. 2009. Estimating groundwater seepages to St. Lucie Estuary. Proceedings, World Environmental and Water Resources Congress 2009: Great Rivers, American Society of Civil Engineers, Kansas City, Missouri, May 17-21.

Question5. Does the combined evaluation of empirical and simulated data adequately link hydrology to biological resources?

The Panel findings and recommendations are presented according to biological and hydrological considerations:

Biological Considerations:

The biological resources are properly linked to salinity. If the model has the salinity correct then there is adequate linkage.

The focus on freshwater flow to keep the oligohaline zone within a region of the North Fork, St. Lucie River between the Prima Vista and Kelstadt bridges should provide a good start for recovery of key faunal elements. However, there may be other factors involved in controlling the recovery or response of the key species. For example, submerged aquatic vegetation (SAV) may still be limited by water clarity and substrate quality, which will likely not be affected by the planned project. Oysters may be limited by substrate quality, lack of hard substrate for larval settlement, and disease/predation pressures (Dame 1996). While salinities lower than 8 psu reduce oyster growth, they may extend further into the North Fork, St. Lucie River than the draft shows and could extend into the 5-psu habitats, if suitable substrate is available. This may lead to more recruitment area further up river.

One reference to consider is: Dame, R. F. 1996. Ecology of marine bivalves, an ecosystem approach. CRC Press, New York. 254 Pp.

Hydrological Considerations:

An analysis of the existing water quality data in the St. Lucie River Estuary is missing from the draft report. As discussed at the workshop on June 2-3, 2009, description of existing water quality in the St. Lucie Estuary should be added in the Final Report. Note that in October 1990, the SFWMD began monthly sampling for physical parameters, nutrients, photosynthetically active radiation, and chlorophyll a at 10 sites within the St. Lucie Estuary (p. 4-18 of the Draft Report). A map showing some of the water quality monitoring stations is attached (Figure 3, next page).

Figure 3. Water quality monitoring stations in the North Fork of the St. Lucie River watershed.

Water quality data at these stations, e.g. SE 01, SE 02, SE 06, SE 12, and SE 13 are readily available from SFWMD's DBHYDRO database. They should be analyzed to document the current water quality conditions.

While the concept of ETM (Estuarine Turbidity Maximum) is the key to the biological aspect of this study, Figure 6-5 should be expanded to better demonstrate the relationship between salinity, total suspended solids, and chlorophyll *a* levels in the water column of the estuary. The following figure (4) shows the spatial profiles of salinity and total suspended solids (in a two-layer fashion) in the Sacramento-San Joaquin Delta, CA (Lung 2001). The turbidity maximum is located immediately downstream of the salinity intrusion. Using the data from DYHYDRO, one could produce longitudinal profiles of salinity and total suspended solids in the St. Lucie Estuary.

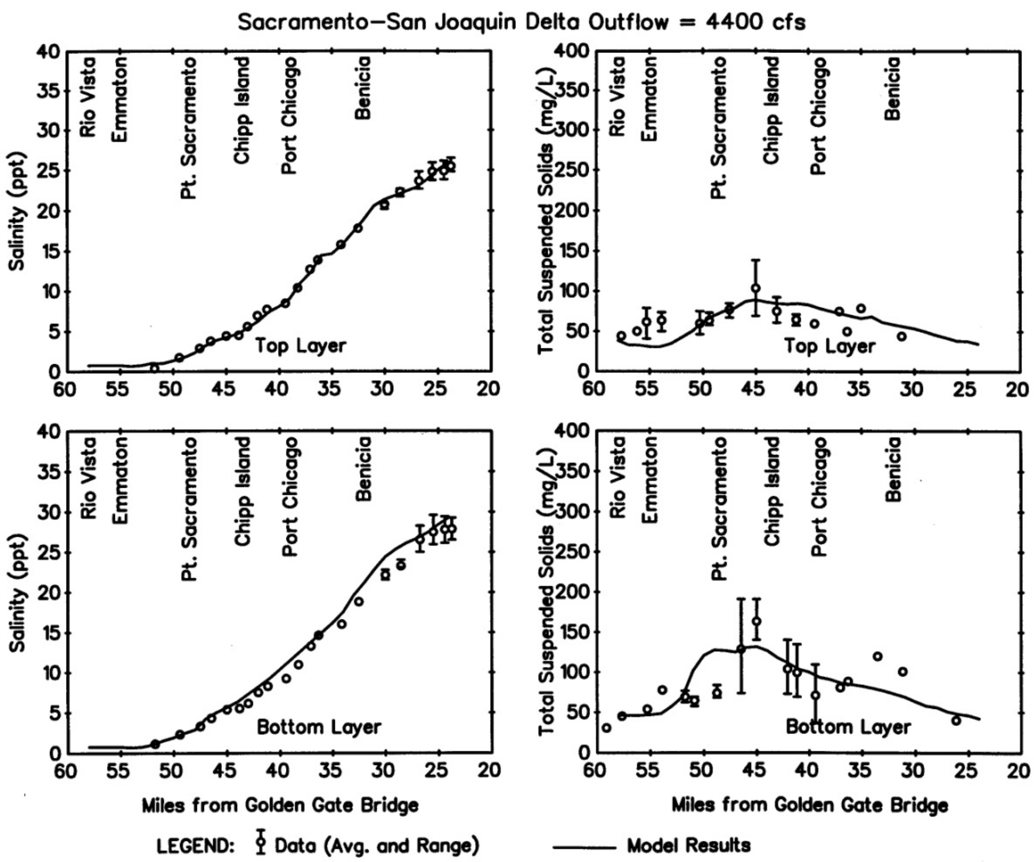
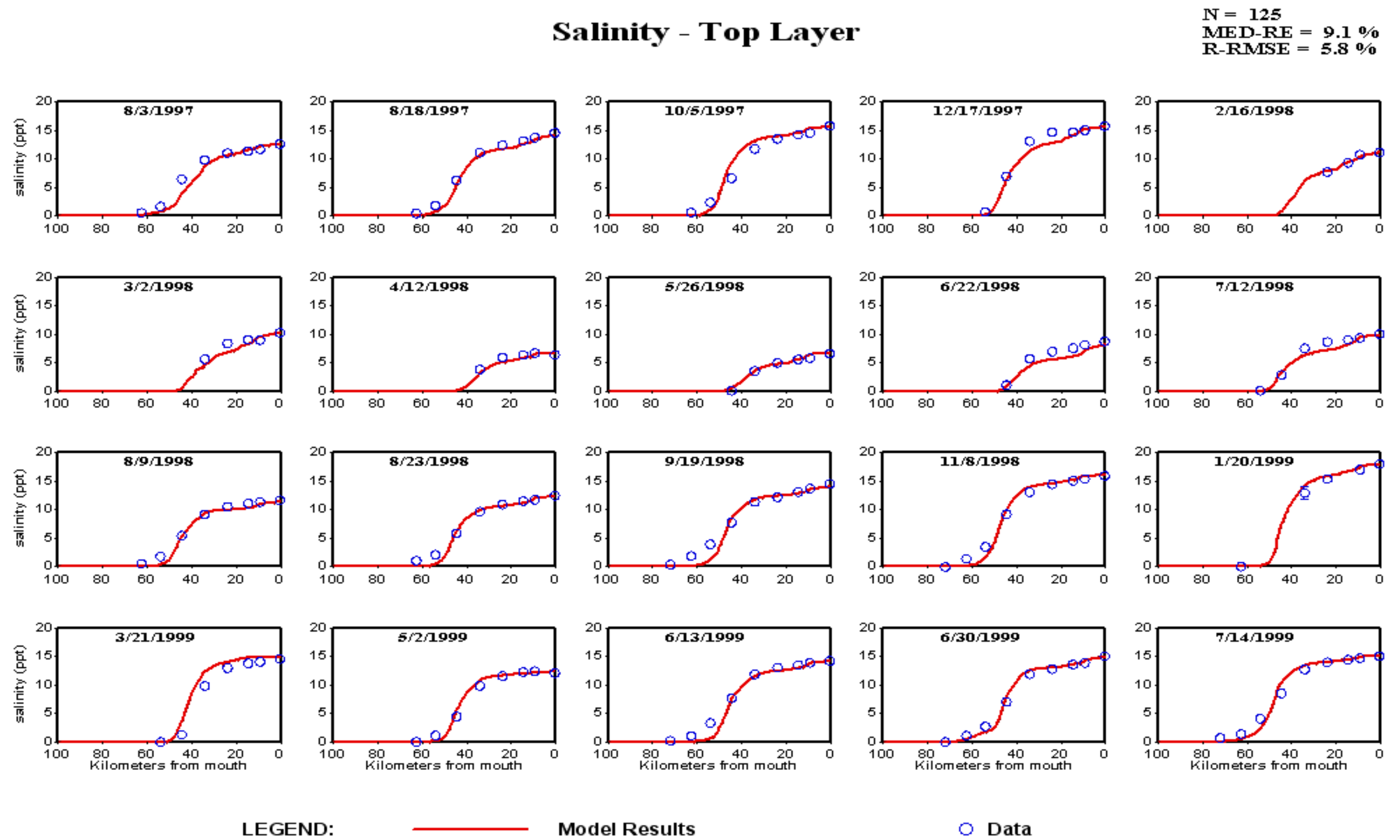


Figure 4. Water quality attributes from a California estuary.

Another figure (5), below, showing the spatial plots of salinity and chlorophyll *a* in the Patuxent Estuary, MD also demonstrates that the location of algal biomass (in terms of chlorophyll *a* levels) is closely related to that of salinity tail. Plots such as these using the data from the St. Lucie will substantially enhance the ETM concept in the St. Lucie Estuary.


Salinity - Top Layer
N = 125
MED-RE = 9.1 %
R-RMSE = 5.8 %
8/3/1997
8/18/1997
10/5/1997
12/17/1997
2/16/1998
3/2/1998
4/12/1998
5/26/1998
6/22/1998
7/12/1998
8/9/1998
8/23/1998
9/19/1998
11/8/1998
1/20/1999
3/21/1999
5/2/1999
6/13/1999
6/30/1999
7/14/1999
salinity (ppt)
Kilometers from mouth
LEGEND:
Model Results
Data

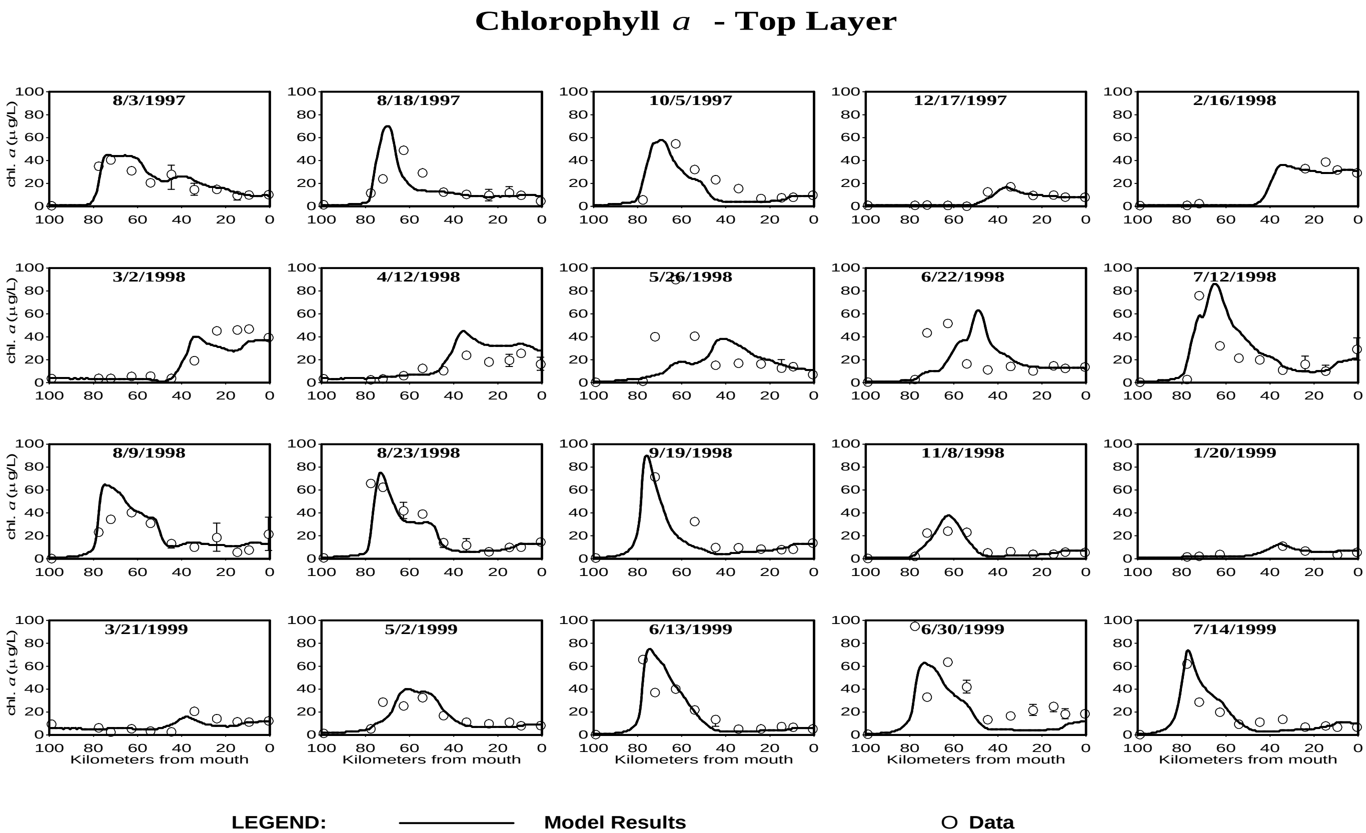


Figure 5. Salinity and chlorophyll a in a Maryland estuary.

<u>Question 6. Does the analysis provide a sound technical basis for reserving water in such locations and quantities, and for appropriate seasons of the year, to ensure protection of fish and wildlife?</u>

Yes, the analysis provided in the draft report does provide a sound technical basis for reserving water to protect targeted fish and wildlife, and also other supporting populations. The basic strategy of pulsing water fits in with ecological theory.

Pulsed events are characteristic of many ecological systems (Odum 1971, Odum 1981), in particular estuarine systems such as the St. Lucie. In order to better understand and manage freshwater flow within this system, data on naturally occurring pulsed events need to be collected to determine how the system will respond both physically (this includes the hydrography and salinity) and biologically (this includes the benthic and planktonic compartments). This information would then feed into developing an adaptive management strategy for executing the pulsed flow regime. (See response to Question 1 for details on ecosystem pulsing.)

Time of year that spawning and habitat use occur for key species need to be summarized based on available reports and determined where unknown. Current plan for three months of flow pulsing (April, May, June) needs to be linked with key species spawning and recruitment periods. A table listing the key species of interest with life-stage, salinity, and time of year present within the North Fork, St. Lucie River is needed in the final version of the technical document. Details in this table need to assess and describe life-history characteristic of key target species (see Question

8 for details of this table). Remember to consult U.S. Fish and Wildlife Service Species and Habitat Profile publications.

The draft Technical Document to Support a Water Reservation Rule for the North Fork of the St. Lucie River states that there will be a one in ten year chance of not meeting pulse requirements during dry periods. How this would affect the North Fork, St. Lucie River needs to be considered. During dry periods the entire Indian River system would likely be affected. Within the adaptive management plan special consideration needs to be given to how flow pulsing would be handled and how the ecosystem would respond. It is especially important to consider the St. Lucie watershed as part of a larger regional watershed in dry times.

References of pertinent articles for the discussion in the report include:

Odum, H.T. 1971. Environment, power, and society. New York: Wiley-Interscience.

Odum, E.P. 1981. The effects of stress on the trajectory of ecological succession. Pp. 43-47 In: Stress effects on natural ecosystems, G.W. Barrett & R. Rosenberg (eds.), Chichester: John Wiley & Sons.

<u>Question 7. Is the methodology used to quantify the water to be reserved scientifically sound and appropriate for this application given the assumptions and constraints?</u>

Yes, a statistical analysis of the simulated daily discharge values is an appropriate and scientifically sound method for determining the quantity of water to be reserved. However, as discussed below, some additional considerations are recommended.

Findings for Sections 8 and 9 of Draft Technical Document

The percent of time that water required to meet the 130 cfs target for the protection of fish and wildlife will be available is quantified in sections 8 and 9 based on the discharge values simulated using WaSh and OPTI-6. The daily discharge values simulated by the WaSh and OPTI-6 models for the 41-year simulation period were converted to mean monthly flow values for the year 2050 with and without the project. The monthly flow values were sorted from the lowest to highest using the Cunnane plotting position method to determine the probability of exceedance for each monthly flow (p. 8-2). The results are plotted in terms of discharge versus percent of time flow equaled or exceeded in three plots, one for all flows, one for wet season flows, and one for dry season flows (Figures 8.1–8.3). Based on the dry season plot, which represents the period from November 1 to May 31, it is concluded that the dry season target of 130 cfs mean monthly discharge at the Gordy Road structure can be met or exceeded 90.5 percent of the time, based on the 41-year simulation (Figure 8.3).

Recommendations for Sections 8 and 9

In general, sections 8 and 9 of the draft technical report need to be expanded to the same level of detail and explanation provided in Sections 1-7. Specific recommendations are as follows:

- The section describing the “Flow Target Calculation” (lines 21-33, p. 8-1) seems out of place. Determination of the target value of 130 cfs is already described in section 7, so it is confusing to describe its calculation again in section 8.

- The Cunnane plotting position method (line 8, p. 8-2) needs to be referenced, i.e., to Cunnane (1978) [this method is also described by Bedient and Huber (2002)], and the selection of the values chosen for the coefficients in the equation (line 8, p. 8-2) needs to be explained and justified.

- In all three discharge versus percent exceedance plots (Figures 8.1 – 8.3), the simulated mean monthly flows decline precipitously at or near the 90 percent exceedance value. Why does this happen? This needs to be explained.

- The discharge values plotted in Figures 8.1–8.3 are the individual, mean monthly values that were calculated based on the WaSh and OPTI-6 simulated daily flows. In effect, one data point from a 41-year period of record is used to determine that the percent exceedance of 130 cfs will be 90.5% (Figure 8.3). A more rigorous analysis of the discharge versus percent exceedance values might produce different results for the percent of time (more or less than 90.5%) that the 130 cfs target can be met. At a minimum, the horizontal axis in Figures 8.1-8.3 should be a probability axis instead of an arithmetic axis. Arithmetic-probability and log-probability plots of the discharge versus exceedance values would better indicate the statistical distribution of the low flow values that were simulated using WaSh and OPTI-6. Curve-fitting based on two-parameter distributions that consider the mean and standard deviation of the low flow data for an assumed arithmetic-probability distribution and on the mean and standard deviation of the logarithms of the low flow data for an assumed log-probability distribution should be done. Other, three-parameter, distributions that also consider the value of the skew of the discharges such as the Pearson and Gumbel distributions could be considered as well. A statistical analysis of the low flow data will not change the distribution of the simulated flows, of course, but it will increase the accuracy of the percent exceedance of the flow that will meet the target value of 130 cfs.

- The 90.5% exceedance that the target flow can be met during the dry season each year indicates that there is approximately a 9.5% probability each year (or approximately a 1 in 10 chance) that the target flow cannot be met. What is the implication of this result, i.e., are there established standards of reliability for water resource projects such as this to which this result can be compared? (See discussion under Question 6, also.)

  Pertinent references include:

Bedient, P. D., and Huber, W. C. 2002. Hydrology and Floodplain Analysis, Third Edition, Prentice Hall, 763 pp.

Cunnane, C. 1978. Unbiased plotting positions: a review. Journal of Hydrology 37:205-222.

Question 8. What additional work, if any, should be considered to enhance the technical basis for quantifying water needed to protect fish and wildlife in future updates of the water reservation?

It is clear that additional information from the scientific literature (including unpublished agency reports) and also research and monitoring data could be acquired immediately, at a reasonable level of effort, that would enhance the scientific basis for the present water reservation proposal and the evaluation of its performance when implemented. We commend the enthusiasm and focus of District staff concerning the potential to initiate expanded or new studies (library, field) to document the ecosystem. Below we consider more immediate information needs relative to the final technical report and longer-range issues, including follow-up studies to fill data gaps.

Additional work recommended to enhance the technical basis includes:

- Demonstrate the ETM (Estuarine Turbidity Maximum) concept for the St. Lucie Estuary by plotting salinity, total suspended solids, and chlorophyll a data in the water column using site-specific data from DBHYDRO (please see response to Question 3).

- The impacts that submarine groundwater discharge (SGWD) and recirculated seawater have on the assumptions made for the groundwater inflow boundary condition in the hydrodynamic model (CH3D) need to be examined further. For the present, relevant results in technical reports and published literature should be reviewed and included in the final technical document as appropriate. In the future, additional measurements of SGWD flows and salinities in the St. Lucie River and Estuary should be made (please see response to Question 4).

- Clarify the open boundary salinity conditions in hydrodynamic model predictions (please see response to Question 4).

- Perform a data analysis of currently available data to document the existing water quality conditions of the study site (please see response to Question 5).

- Sections 8 and 9 of the draft technical report need to be expanded to the same level of detail and explanation provided in sections 1-7 (please see response to Question 7).

- A more rigorous analysis of the simulated low flows, including statistical analysis and curve-fitting for assumed arithmetic and logarithmic distributions of the low flows, should be carried out to improve the accuracy of the prediction for the percent of time (91.5%) that the target discharge of 130 cfs will be met (please see response to Question 7).

- Knowing when key resource species spawn and recruit to the North Fork, St. Lucie River will be central to the ecological success of the project. Summary tables that list key species with some information on preferred salinity ranges, habitat use by life stage, period of the year present within the system, and ecological importance would be helpful. Many species are referred to in the document but there is no central location that lists them all. The key species listed in the draft Technical Document to Support a

Water Reservation Rule for the North Fork of the St. Lucie River include the following: Shoreline and floodplain vegetation, SAV (submerged aquatic vegetation), oysters, benthos (freshwater and marine species, various taxa), larval and juvenile of fish species including drum, sand seatrout, naked gobies, other gobies, anchovy, ladyfish, snapper, snook, pipefish, hogchoker, spotted seatrout, silver perch, croaker, flounder, filefish, and puffer. The report should be sure to include scientific names for species, genera and families of organisms. (Please see Question 1.)

- When completed the study on zooplankton and other valued ecosystem components needs to be included in the report.

- An important aspect of the future evaluation of the project's ecological performance will be the monitoring program. While the PIR document has a some detail on a draft monitoring plan, this information needs to be incorporated into the draft technical document . The monitoring plan is the central focus of any future evaluation to quantify water needs to protect fish and wildlife. Careful attention needs to be paid to sampling design and statistical robustness. An outline of design for the monitoring needs to be included in the report's executive summary as well. This will be the best vehicle for ensuring fish and wildlife goals are meet. And it will be a key component of any adaptive management strategy. Linkage of hydrology, freshwater pulsing to move the 1 psu isohaline between the Prima Vista and Kelstadt brides, with ecological response, primarily larval and juvenile fishes and their condition index, will be the principal goal for the monitoring program. Therefore, sampling design will be critical to successful use of resources.

- A major part of the monitoring plan needs to be devoted to justifying the performance measures that will be used for assessing ecosystem response of both the benthic and pelagic components of the ecosystem. In the future, models of the biological energy flow through the North Fork, St. Lucie River should be developed. The approach should be similar to Ulanowicz (1986), Baird and Ulanowicz (1989), and Baird et al. (2004). These are network analyses that quantify food webs and describe the biotic energy flows of an ecosystem. These models are static but allow inference about physical dynamics and consequences of changing physical parameters. A good example is found in Baird et al. (2004) with application to effects of hypoxia on trophic transfer. These models rely on principles of conservation of mass or energy and need data on inputs of organic carbon, biomass of all major functional compartments of the ecosystem, diets of predators, and transfer efficiencies (typically production/biomass ratios from the literature) to balance the system (Ulanowicz 1986). The result is a system of flows that permits the description of the fate of organic carbon as it moves through the food web and of the structural properties of the flows, which imply characteristics of system dynamics (Baird et al. 2004). To simplify the system, species can be pooled into compartments by trophic similarity. Details on this modeling approach can be found at http://www.ecopath.org/ and at http://www.cbl.umces.edu/~ulan/ntwk/network.html.

  See also:

Baird, D. and R. E. Ulanowicz. 1989. Seasonal dynamics of the Chesapeake Bay ecosystem. Ecological Monographs 59:329–364.

Baird, D., Christian, R.R., Peterson, C.H., and Johnson, G.A. 2004. Consequences of hypoxia on estuarine ecosystem function: Energy diversion from consumers to microbes. Ecological Applications 14:805-822.

Ulanowicz, R. E. 1986. Growth and development: ecosystem phenomenology. Springer-Verlag, New York, New York.

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Appendix A-2.
Other Public Comments

Note: Other than minor formatting, these documents have not been changed from what was submitted to the Water Reservation Rule for the North Fork of the St. Lucie River WebBoard discussion.

North St. Lucie River Water Control District (NSLRWCD)

Technical Questions for SFWMD's May 2009 Draft Report: Technical Documents to Support a Water Reservation Rule

1. Table 7.3 on Page 7-16 states an objective of maximizing the flow to the Ten Mile Creek. As discussed on separate forums with the Army Corps of Engineers and South Florida Water Management District there is a substantial lack of maintenance on Ten Mile Creek and as of now it cannot currently handle the proposed flows.

   Lines 27 – 31 on Page 7-17 indicates that the proposed rerouting of flows to the North Fork as part of the Indian River Lagoon-South Project in the "2050 Future with Project Condition" will increase annual flows through the North Fork via the Gordy Road Structure. Again, this raises concerns about maintenance needs in Ten Mile Creek to increase the current capacity of the creek to handle the increased flows.

2. In Lines 18 – 24 on Page 7-24, there is mention of the need for "pulse releases" in times other than the dry season, as well as a need for environmental monitoring with these releases. What parameters other than salinity levels, if any, are of concern in these potential scenarios?

3. Figure 9.1 on Page 9-2 provides a volume probability curve for the "2050 Future with Project Condition", quantifying the percentage of time that surface water volumes are expected to be reserved (or required) in the dry season for delivery into the North Fork at the Gordy Road Structure. It appears that this data assumes that the Indian River Lagoon-South Project is constructed in its entirety. In the event that portions of the Indian River Lagoon-South Project are not constructed what impacts does the proposed reservation have on supplemental irrigation demands and legal water use needs, including the NSLRWCD Diversion and Impoundment Permit which back pumps water from Ten Mile Creek.

4. Lines 6 – 17 on Page 7-23 contains, language on Supplemental Irrigation Supply. NSLRWCD provides water for irrigation and drainage needs throughout the entirety of the NSLRWCD boundary. Based upon Figure 4.6 on Page 4-15 the Ten Mile Creek Basin does not appear to include the entirety of the NSLRWCD boundaries upstream of the Gordy Road Structure for irrigation.

   Table C3-4 in Appendix C on Page C-30 refers to the protection of existing irrigation demands, and illustrates how basins were modeled to simulate these existing water uses. However, the basin areas appear to only be focused on users of SFWMD canals in these areas and the users of water in the North and South Forks of the river. It does not appear that the existing water demands of the western half of NSLRWCD (approximately 30,000 ac), which use surface water upstream of Ten Mile Creek were included in the current modeling efforts.

Comments on the Technical Document offered by Carl Woehlcke.

For those of you who do not know me, I am an economist and was for many years an employee of the South Florida Water mp Management District. Thus, I cannot speak to many of the technical considerations that go into the review of the science behind this document. What I hope to offer is some perspective on the framework within which this document can be considered.

Here are some concerns:
1. Both the evaluation of historical and future conditions seems to be based on those considered and the Indian River Lagoon Feasibility Study. Yet, the existing conditions in that area, and the expected future conditions have been moving away from the land-use and land cover assumptions used in the Indian River Lagoon Study. Historically, during dry periods, water used by citrus was of paramount importance. One pattern is that water would be withdrawn from the canals for irrigation purposes down to a set allowed level. I believe that the typical irrigation used in that area was called crown flood, and involved sequentially flooding ditches and letting water seep into the soil underneath the canopy of the trees. I believe that this use tends to tie up a large amount of water in the application process. A second aspect of citrus irrigation was that during dry periods, Florida aquifer wells would be allowed to flow bringing additional, albeit brackish, water to the surface water system. Recent developments, including citrus disease problems and competition with urban land uses, indicate that the continuation of this pattern into the future is not likely. This will have a number of effects on water use and run-off especially during the dry season. Less Floridan aquifer water may be brought to the surface, on the other hand, the evapotranspiration of replacement land uses may well be less than that of citrus and water table levels may not need to be maintained. For the most part, the land-use most likely to replace the citrus is urban, furthermore, additional development is expected in areas already slated for urbanization, especially the city of Port St. Lucie, which lies on either side of the section of the North Fork where the fresh water flows are being analyzed. Not only will the urbanization effect runoff characteristics, but, because the water used by utilities in St. Lucie County is almost all brackish Floridan water, and because virtually all of this water will be used for irrigation purposes (either directly or as reclaimed water, this may well have a significant impact on the amount and timing of water going to tide it in this area, especially during the dry season. I wonder whether and how these considerations have been taken into account in the analysis.

2. I was somewhat surprised that the District was proposing reservations in the St. Lucie/IRL area, because the primary problem in that area has been considered to be excessive water to tide. In fact, a significant portion of the expenditures associated with the IRL CERP project are associated with the purchase and rehydration of lands within the basin. One of the major benefits cited for this rehydration is that it would increase the evapotranspiration and hence reduce runoff. I understand that the District is constrained by state/federal agreements to provide assurances that water in the CERP plan to to be used for environmental purposes will be there when it is desired to be used. In the technical document, it is shown that significant additional water is moved to come in to the North Fork to help maintain flows. It is not clear that if there is need for water is to increment those flows, that this water might not be made available from the project by changing assumed operating criteria.

3. I see that some questions were raised about boundary conditions, as it relates to maintaining areas of low salinity. To this, I offer the following additional consideration. At the south end of the target area for maintaining low salinity is the outlet to tide from the C-24 canal. It would seem to me that outflows from that canal might also have a significant effect on the salinity upstream, especially if those releases occurred during incoming tides so that the released freshwater would move upstream. The first point above indicates that there might be an additional flows to tide from urbanized areas during the dry seasons related to lower evapotranspiration in urban areas, and to the additional water brought to the surface water system from the Floridan aquifer.

4. Lastly, I am concerned that there is a weakness in the frequency distribution curve approach. I believe that the salinity effects on the environment relate to a very short timescale. Since the frequency distribution curve reflects an evaluated result, over a multiyear period would it not ignore variations in the number of years and the time periods within each year when the flows fall short of the target. If the percent of time that the target flows are not met are grouped in a couple of years, the overall environmental result could be very different than if it were spread out over a much larger number of years, where each of the periods of higher salinity was just long enough to cause significant negative environmental effects?

Comments on "Draft Report: Technical Document to Support a Water Reservation Rule for the North Fork of the St. Lucie River," May 2009, South Florida Water Management District

June 10, 2009

Prepared by Lorraine Heisler and Steve Schubert, US Fish and Wildlife Service, South Florida Ecological Services Office.

US Fish and Wildlife Service (Service) staff have reviewed the draft technical document and offer the following comments. These comments focus on technical suggestions to improve the document and do not present an official position of the U.S. Fish and Wildlife Service. If you have questions or need further information, please contact Steve Schubert (772)-562-3909, ext 249, steve_schubert@fws.gov; or Lorraine Heisler (772)562-3909 ext 264, lorraine_heisler@fws.gov. Thank you for this opportunity to comment on the draft.

1. Figure 7-2; Pages 7-6 and following pages

   Discussion at the peer-review workshop on June 2 indicated that there is scientific uncertainty about the ecological response to pulsed flows. Given that operations will be adjusted in response to actual project performance, it would be valuable to confirm that the volume of water being proposed for the reservation is not dependent on the specific operations assumed in the modeling. We suggest an additional simulation be run that assumes a constant dry season flow of 130 cfs. This would provide a check that the flows proposed for the reservation are sufficient to move the oligohaline zone downstream with or without pulsed operations.

2. Figures 8.1 and 8.3 (Pages 8-3 and 8-5)

   These volume probability curves illustrate the without project, with project, and target flows into the North Fork and measured at Gordy Road. In both figures the blue trace showing the target has a break point at approximately the 90th percentile, above which the line drops quickly from 130 cfs to less than 50 cfs, then to zero. This differs from the way targets have been defined in other technical reports used to quantify water for fish and wildlife and restoration (e.g., for the Picayune Strand and Kissimmee River/UCOL technical reports). If the ecological rationale is that 130 cfs is the "amount of fresh water needed to be delivered by the Ten Mile Creek (Gordy Road Structure) during the dry season to protect larval and juvenile fish habitat within the North Fork," (Page 8-1, lines 17-19), then the target trace of 130 cfs should continue out to the 100th percentile of the volume probability curve, regardless of whether or not water is available during all portions of the dry season. We suggest that the target trace of 130 cfs be extended to the 100th percentile. This would not affect the quantification of water to be reserved, as that would be the lesser of either the target or the actual delivery from the project. However, it would avoid inconsistency with previous applications of volume-probability curves, and prevent the mistaken interpretation that very low (even zero) mean monthly flows are desirable "targets."

3. Salinity Tolerances of Species

During the June 2 workshop, panel members suggested that the report include additional information on the salinity tolerances of species in the SLE. We refer you to one potentially helpful source, "Ecological and Hydrologic Targets for Western Biscayne National Park," (SFNRC Technical Series 2006:1). This report was developed by the National Park Service, South Florida Natural Resources Center and Biscayne National Park, and compiles and synthesizes information from the primary sources on salinity requirements for several species, including spotted seatrout, mojarra, silver perch, and eastern oyster. A copy can be obtained from the SFNRC at Everglades National Park.

4. The review panel suggested that the available Habitat Suitability Indices (HSIs) be consulted for additional biological information that may add scientific support for the Water Reservation. The HSIs are available for a number of species that may be present in the St. Lucie River and Estuary at the following website: http://www.nwrc.usgs.gov/wdb/pub/hsi/hsiindex_bynumber.htm

The specific links to selected species follow:

•**82(10.20)** (1655 KB)
•Stickney, R.R., and M.L. Cuenco. 1982, Habitat suitability index models: juvenile spot: U.S. Fish and Wildlife Service Biological Report 82(10.20). 12 pp.

•**82(10.21)** (2322 KB)
•Diaz, R.J. 1982, Habitat suitability index models: juvenile Atlantic croaker: U.S. Fish and Wildlife Service Biological Report 82(10.21). 22 pp.
•**82(10.98)[Revision – originally printed as 10.21]** (1835 KB)
•
•Diaz, R.J., and C.P. Onuf. 1985, Habitat suitability index models: juvenile Atlantic croaker [revised]: U.S. Fish and Wildlife Service Biological Report 82(10.98). 23 pp.

•**82(10.31)** (1868 KB)
•Sikora, W.B., and J.P. Sikora. 1982, Habitat suitability index models: Southern kingfish: U.S. Fish and Wildlife Service Biological Report 82(10.31). 22 pp.

•**82(10.57)** (2489 KB)
•Cake, E.W., Jr. 1983, Habitat suitability index models: Gulf of Mexico American oyster: U.S. Fish and Wildlife Service Biological Report 82(10.57). 37 pp.

•**82(10.58)** (1752 KB)
•Pardue, G.B. 1983, Habitat suitability index models: alewife and blueback herring: U.S. Fish and Wildlife Service Biological Report 82(10.58). 22 pp.

•**82(10.74)** (1392 KB)
•Buckley, J. 1984, Habitat suitability index models: larval and juvenile red drum: U.S. Fish and Wildlife Service Biological Report 82(10.74). 15 pp.

•**82(10.75)** (1870 KB)

•Kostecki, P.T. 1984, Habitat suitability index models: spotted seatrout: U.S. Fish and Wildlife Service Biological Report 82(10.75). 22 pp.

•82(10.76) (1671 KB)
•Mulholland, R. 1984, Habitat suitability index models: pink shrimp: U.S. Fish and Wildlife Service Biological Report 82(10.76). 17 pp.

•82(10.77) (1807 KB)
•Mulholland, R. 1984, Habitat suitability index models: hard clam: U.S. Fish and Wildlife Service Biological Report 82(10.77). 21 pp.

•82(10.92) (2095 KB)
•Enge, K.M., and R. Mulholland. 1985, Habitat suitability index models: Southern and gulf flounders: U.S. Fish and Wildlife Service Biological Report 82(10.92). 25 pp.

•82(10.151) (1481 KB)
•Palmer, W.M., and C.L. Cordes. 1988, Habitat suitability index models: diamondback terrapin (nesting) – Atlantic coast: U.S. Fish and Wildlife Service Biological Report 82(10.151). 18 pp.

5. Adaptive Management

The peer review panel discussed the need for adaptive management to assess and improve the response of the oligohaline zone to the project's flow regime. We recognize that the water reservation is only a component of the overall implementation of the IRL-S Project. A monitoring and assessment plan is in place for flow and water quality in the St. Lucie River and Estuary system. In the future, there will be additional periodic opportunities to address the efficacy of the monitoring and assessment plan.

Appendix A-3.
Summary of Peer Review Panel Recommendations, Public Comments and Responses

Peer Review Panel Recommendations

General

1. Summarize the conclusions stated in different sections of the report in the Executive Summary

   The Executive Summary has been rewritten to better summarize the background and conclusions of the report.

2. Globally replace the term "ppt" (parts per thousand) with "psu" (practical salinity unit) throughout the document to reflect current terminology.

   This has been completed.

3. The connectivity of the North Fork of the St. Lucie River to the greater regional ecosystem and broader plans for restoration needs a more explicit description.

   A better summary of the role of the North Fork of the St. Lucie River in the overall restoration plan for the Everglades has been added to Section 3.

4. The document could be enhanced by the inclusion of additional references and discussion of the technical literature. Almost 50 references were provided by the Peer Review Panel to include in the document

   The authors thank the panel and have included many of the suggested references in the final document.

Adaptive Management & Monitoring Plan

5. Develop a plan for evaluating how the water reservation will perform, both physically and biologically in terms of meeting ecological goals and objectives (stated in ways that success can be measured objectively and quantitatively) to protect fish and wildlife during dry periods.

   Protocols for monitoring, adaptive management, and operations are not part of the water reservation rule development process. Such plans to address the performance of the water reservation will be addressed in the operations plan that will be refined as part of detailed project design and coordinated within CERP monitoring and assessment programs. For further information, see the general discussion added in Section 7.6, Future Monitoring and Performance Assessment.

6. Within the Adaptive Management Plan special consideration should be given to how flow pulsing would be handled.

   The operational and hydrologic details associated with delivery of pulsed flows are not addressed in this technical document (see response to comment #5). The importance of adaptive management and monitoring associated with flow pulsing in successful implementation of the water reservation is recognized and will be addressed in an operation plan as part of the detailed project design. See also general discussion added in Section 7.6, Future Monitoring and Performance Assessment, and the expanded discussion of flow pulsing in Section 5.1.3.1.

7. A major part of the monitoring plan needs to be devoted to justifying the performance measures that will be used for assessing ecosystem response of both the benthic and pelagic components of the ecosystem.

   A discussion of uncertainty associated with the performance measure has been added to Section 7.5.1. The protocol for monitoring and development of an adaptive assessment plan are not part of this water reservation rule development. Identification and justification of performance measures will be addressed in the operations plan as part of the detailed project design and coordinated within CERP monitoring programs. See general discussion added in Section 7.6, Future Monitoring and Performance Assessment.

Section 4 (Description of the Watershed)

8. An analysis of the existing water quality data in the St. Lucie River Estuary should be added to the final report. Use currently available published reports.

   Section 4.8, Water Quality, has been revised to present more information regarding water quality in the St. Lucie River Estuary.

Section 6 (Identification of Fish and Wildlife to be Protected)

9. Provide a more detailed discussion explaining why other potential VECs (e.g., SAV, oysters, shoreline vegetation, larval and juvenile fishes) were dropped from consideration.

   This information has been added to Section 6.1.

10. Add the language and references provided at the top of page 13 of the Peer Review Panel's report to Section 6.2 of the document which discusses the ecological importance of the low salinity zone.

    This information and the references were added to Section 6.2.

11. Data from the St. Lucie system for benthos, fish eggs and larvae are sparse and need to be augmented in the water reservation project.
    a. Provide a summary of the recently collected zooplankton data obtained from the North Fork of the St. Lucie River to the final report.

       This information has been added.

    b. Section 6 should also include a table listing key species that utilize the North Fork's low salinity zone including information on life-stages, salinity tolerance limits, habitat needs and time of year present within the in the estuary.

       Please see Table 6.1, which was added in response to this recommendation.

    c. Time of year that spawning and habitat use occur for key species need to be summarized from available reports. The current plan for 3 months of pulsed flows (April, May and June) need to be linked with key species spawning and recruitment periods.

       This has been completed for the entire dry season (November 1 – May 31).

12. The final document needs to include a section that discusses the ecological importance of pulsed flows. Add the text and references provided by the peer review panel (see bottom of page 8).

    Section 5.1.3.1, Pulsed Inflows, has been expanded and revised to include a discussion of the ecological importance of pulsed flows. Also see the response to Comment #11b above and the resulting Table 6.1.

13. Discussion of the estuarine turbidity maximum should be expanded to better demonstrate the relationship between salinity, total suspended solids, and chlorophyll *a*. (DBHYDRO data could be used to produce longitudinal profiles of salinity and total suspended solids in the St. Lucie Estuary).

    In future updates of the water reservation rule, additional data will be provided to further demonstrate the relationship between the estuarine turbidity maximum and these parameters. For further information, see Section 9.2, Periodic Update of Technical Document and Rule.

14. Figure 6.5 should be expanded to better demonstrate the relationship between salinity, total suspended solids, and chlorophyll *a* levels in the estuary. Consider using DBHYDRO data to produce longitudinal profiles of salinity and total suspended solids in the St. Lucie Estuary (see example figure 4 and on pages 23 & 24 of Peer Review Panel Report).

    The suggestions are appreciated and expanded use of existing observations to create figure representation as suggested will be considered in the technical documentation associated with future updates of the water reservation rule see Section 9.2, Periodic Update of Technical Document and Rule.

Modeling Technical Issues (Section 7), *CH3D Hydrodynamic Model*

15. Open water boundary salinity condition. Not clear what kind of advection scheme was used to derive the open water boundary during ebb tide. Staff should clarify the open water boundary condition issue discussed at the workshop (see pages 15-16 of Peer Review report)

    Uncertainties at open boundaries conditions are well known in hydrodynamic/salinity modeling. The approach used by this study is very conventional and used in many other studies (Sheng 1986, Sheng and Davis 2003). At the ocean boundary, for incoming tide, the salinity is prescribed as ocean water salinity; for outgoing tide, we used a simple upwind (and/or higher order) advection scheme using the following equation:

$$\frac{\partial S_b}{\partial t} + u\frac{S_i - S_b}{\Delta x} = 0$$

    Where Sb is the salinity at the open boundary, Si is the salinity at immediate grid cell. Using a constant value for the incoming tide sometimes can be problematic especially for the period when the tide just turned. One way to do it is giving a certain time for the transition of the salinity value goes to become ocean water salinity value. The uncertainty at the boundary is further mitigated by extending the boundary offshore. The question is how far offshore the boundary should be? It depends on the size of the estuary. Here model tests can be helpful in determining the size of the offshore area which has been part of the calibration process. Salinity results at A1A (Figure 10, Appendix D) indicate that the offshore area is adequate for this model. For further information, see Appendix D.

16. Several questions concerning the quality and quantity of the submarine groundwater discharge that was used as input to establish boundary conditions for the CH3D model need to be addressed, concerning assumptions and sensitivity of the model.

    How much does re-circulated seawater increase the salinity of measured SGWD for the St. Lucie Estuary (review Martin et al. 2007 and Yeh et al. 2009) and how do these results affect the assumptions used in the CH3D model and their results? (page 15 of Peer Review report).

The recirculation of the seawater is commonly found in estuaries as indicated by Martin et al. 2007 and Yeh et al. 2009. For simplicity, the groundwater seepage rate used in the CH3D model is a net groundwater seepage rate. It does not include the re-circulation of the seawater. The 1.2 cm/day seepage used in the model is very close to the 1.3 cm/day average value reported by Belanger et al. (2003). Since the 1.2 cm/day is the net seepage, zero salinity is the right boundary condition. If the re-circulation of the seawater is included, the seepage rate will be substantially larger and non-zero salinity should be used.

17. Present the CH3D salinity results as snapshot spatial profiles (see page 17 of panel report)

    The time-series plots of the 16 monitoring locations throughout the estuary including the inlet area, the mid-estuary, North Fork, and South Fork (Figures D10 to D15) provide similar spatial contrast of salinity changes and model performance as a snapshot spatial profile would do. These figures and statistics demonstrate the strength of our model with good accuracy. Additional ways to present the information will be considered in future revisions (see Section 9.2)

18. Appendix D. The match between model calculated and measured salinity data needs more explanation. Consider adding total freshwater inputs (cfs) to Figures 10-15 to reflect seasonal changes at Prima Vista and Midway bridges – How do they compare? Also need to explain how staff came up with model salinity results (from 4 vertical layers) for comparison with measured data. Also need to explain the difference between modeled versus measured salinity at HR1.

    The flow data from the watershed during the calibration period (1997 to 2005) were presented in Figures D4 and D5. The correlation between the freshwater inflow and salinity is presented. For the stations in the North Fork such as at the Prima Vista and Midway Bridges, it is not surprising that the R^2 is lower when moving upstream. Salinity variation itself is lower upstream due to its proximity to the headwater in the Gordy Road Structure. In addition to statistics, we also use graphics to model performance. Figure 12 shows that the model performed very well in the upstream area at Prima Vista Bridge and at Midway Bridge.

    The model has four layers. During calibration, the modeled data were averaged for Layers 1 and 2 and compare with the surface salinity data. Similarly, Layers 3 and 4 were averaged and compared to the bottom layer of the measured data.

    Overall, the model performed well at the HR1 station. For the period from 1998 to 1999, the model under-predicted salinity when compared with the measured data. It may be due to the accuracy of freshwater inflow data. The predicted salinity matched well with measured data in the remainder of the calibration period.

19. The report conclusions need to include the hydrological details and predicted ecological benefits of flow pulsing based on a synthesis of information on life-stages, salinity tolerance, time of year in the system and habitat needs.

    As stated in response to comment #6, the operational and hydrologic details associated with delivery of pulsed flow are not addressed in this technical document. The importance of adaptive management and monitoring associated with flow pulsing for successful implementation of the proposed water reservation is recognized and will be addressed in an operation plan as part of the detailed project design. Revisions and additional ecological data will be included as part of future updates of the water reservation rule. See Section 9.2, Rule Updates. Additional information, as needed may be collected as part of the operations plan and detailed project design. See general discussion in Section 7.6 and the expanded discussion of flow pulsing in Section 5.1.3.1 For further information, see also the responses to comments #6, 12, 27, 30, and 38 and comment #11 for table 6.1 of life history information.

WaSh Model

20. Uncertainty concerning the impact of not including the Floridan aquifer in the WaSh model should be assessed in the final technical report by comparing the estimated vertical leakage from the Floridan aquifer to the surficial aquifer system in the basin to other water-budget components in the basin.

    The surficial aquifer and the Floridan aquifer are laterally continuous, but are vertically separated by several hundred feet of low-permeability sediments, consisting primarily of clay, dolomite, and micritic limestone. This confining layer can be encountered between about 150 to 700 feet below the ground surface in the project area. A review of regional groundwater models of the area indicates that the vertical hydraulic conductivity (Kv) of this confining unit ranges from 0.0005-0.00001 feet/day. Thus, vertical leakage from the Floridan aquifer to the surficial aquifer is assumed to be insignificant in the WaSh model. This assumption is also used in other surficial aquifer models used in the District.

21. The Panel also recommended that simulated groundwater heads in the WaSh model be compared with groundwater levels from selected wells in the basin as part of a long-term monitoring plan to determine how well the groundwater component in the surficial aquifer is represented in the WaSh model

    Calibration of groundwater levels was conducted during land use parameterization using MicroWaSh (Page C-15) to ensure proper wetland hydroperiod and water levels in major land use types. At the basin level, the major objective of calibration is to match the modeled basin flows with these measured District flow control structures for this model application. Future refinement of the model calibration will include groundwater well data in this watershed.

OPTI-6 Model

22. Add a discussion of the uncertainty associated with OPTI-6 including some indication of how reliable are the simulations (how sensitive are the simulations to real-time day-to-day operation of the reservoir and water control structures?)

    The OPTI model can be modified to add the forecasting functionality to guide day-to-day operation. What we may learn from the model in this project is that the general operational rule of the C-24 STA is to provide continuous water quality improvement and flow delivery into Ten Mile Creek year-round when there is water in the reservoirs while the C-23/C-24 Reservoirs will be operated in a way to be close to the full capacity before the onset of the dry season. The operational protocols associated with the water reservation rule and its monitoring will be addressed as part of the final detailed project design. However, the operational plan will depend on translating the OPTI6 results into day-to-day operations and will not have the same level of accuracy as the models.

23. Provide temporal plots of freshwater inputs to the St. Lucie Estuary, present results as vertical averaged salinity.

    This method of data presentation will be investigated for inclusion in future updates and revisions.

24. It is acknowledged in the draft report that model uncertainty associated with the OPTI-6 is extremely small as long as input data are correct, but that real-time day-to-day operation of the reservoir and water control structures may not be able to achieve the optimal results produced by OPTI-6. Therefore, it is recommended that discussion of this issue be expanded to include some indication of how reliable the simulations are considered to be.

    A limited discussion has been added to the document to address this point; see also the response to comment #22.

Sections 8 & 9

25. Expand Sections 8 and 9 to the same level of detail and explanation provided in Sections 1-7. Include methods of calculation and explanation (page 26a).

    Further information has been added to Sections 8 and 9.

26. The 90.5% exceedance that the target discharge can be met during the dry season implied there is a 1-in-10 chance that the target cannot be met every year. What is the implication of this result and are there established standards of reliability for the performance of water resource projects that these results can be compared? A more rigorous analysis of the simulated low flows should also be carried out to improve the accuracy of the percent of time that the target discharge cannot be met.

    The interpretation of the exceedance curve has been modified to not imply certainty beyond what that the models can provide (see Section 7). It is more appropriate to indicate that the target discharge is met “approximately 90%” of the dry season months. More rigorous statistical analysis of the model output in an attempt to increase the accuracy of the exceedance curve is not warranted and may convey a false sense of certainty given the limitations of the models that produced the data. As far as the probability of not meeting the target for every year, the remaining 10% of the dry season months when the target is not met – ranked regardless of year –- should not be interpreted as a 1-in-10 probability of not meeting the target for every year.

Recommendations for Future Work

27. In order to better understand and manage freshwater flow within this system, data on naturally occurring pulsed events need to be collected to determine how the system will respond both physically (includes hydrography and salinity) and biologically (includes benthic and planktonic compartments). This information would feed into developing an adaptive management strategy for executing the pulsed flow regime.

    Data are currently being collected as are presented in Section 6.6. Additional information will be assessed and included in technical documentation associated with future updates of the water reservation rule (See Section 9.2) and be used to aid in the development of the adaptive management strategy. If appropriate, additional monitoring may be included in the monitoring plan to assess operations. See general discussion added in Sections 7.6 and 5.1.3.1 and responses to comments #6, 12, 19, 30, and 38.

28. In the future, models of the biological energy flow through the North Fork, St. Lucie River should be developed as a means of assessing the ecosystem response to the project and also for assessing long-term change within the St. Lucie system.

    This not currently part of the future work plans. Staff will consider the use of such models in the next update of the rule.

Comments from North St. Lucie River Water Control District

29. The Project will increase annual flows through the North Fork via the Gordy Road Structure. This raises concerns about maintenance needs in Ten Mile Creek to increase the current capacity of the creek to handle the increased flows.

    This will be addressed in detail in the operations plan that will be developed in cooperation with the North St. Lucie River Water Control District.

30. On Page 7-24, there is mention of the need for "pulse releases" in times other than the dry season, as well as a need for environmental monitoring with these releases. What parameters other than salinity levels, if any, are of concern in these potential scenarios?

    This discussion (Section 7.5.1) states that pulse releases *may be desirable* at other times (other than the dry season) such as in drought conditions or if the onset of the wet season is delayed. Operational flexibility coupled with environmental monitoring will be required during implementation of the water reservation rule. Specific parameters associated with monitoring will be addressed in an operations plan as part of the detailed project design. For further information, see the general discussion added in Section 7.6, Future Monitoring and Performance Assessment and the responses to comments #6, 12, 19, 27, and 38.

31. In the event that portions of the Indian River Lagoon-South Project <u>are not</u> constructed, what impacts does the proposed reservation have on supplemental irrigation demands and legal water use needs, including the NSLRWCD Diversion and Impoundment Permit which back pumps water from Ten Mile Creek?

    The proposed reservation will not be implemented unless the Indian River Lagoon-South Project is built. While the reservation is under consideration for adoption in 2009, the associated criteria will not be developed until the project is operational. As described in Section 2.2, existing legal uses of water are protected so long as they are not contrary to the public interest.

32. Page 7-23 contains language on Supplemental Irrigation Supply. NSLRWCD provides water for irrigation and drainage needs throughout the entirety of its boundary. Based upon Figure 4.6, the Ten Mile Creek Basin does not appear to include the entirety of the NSLRWCD boundaries upstream of the Gordy Road Structure for irrigation.

    Basin boundaries for the Ten Mile Creek basin were determined based on the St. Lucie Watershed Assessment conducted by Coastal Environmental/Post, Buckley, Schuh & Jernigan for the District in 1999. These basin boundaries vary somewhat from the 298 District boundaries defined by the North St. Lucie River Water Control District along their northwest and southwest borders. These sub-basins have the ability to pump water west of the header canal to the C-24 and C-25 Basins for flood protection. For modeling purposes, the District included the two areas in the C-24 and C-25 Basins. Waters in these sub-basins are primarily retained in local canals for water supply during the dry season; while stormwater runoff is pumped into the C-24 and C-25 Basins during the wet season for drainage and flood control purposes. By not including these two sub-basins in the Ten Mile Creek Basin, the WaSh model boundaries may result in a slight underestimation of peak flows at the Gordy Road Structure during the dry season and overestimation of peak flows in C-24 and C-25 Basins during the wet season, which are not critical for this application of the model.

33. Table C3-4 in Appendix C on Page C-30 refers to the protection of existing irrigation demands, and illustrates how basins were modeled to simulate these existing water uses. However, the basin areas appear to only be focused on users of SFWMD canals in these areas and the users of water in the North

and South Forks of the river. It does not appear that the existing water demands of the western half of NSLRWCD (approximately 30,000 ac), which use surface water upstream of Ten Mile Creek were included in the current modeling efforts.

The irrigation demand and supply for the Ten Mile Creek basin (part of the North Fork basin) were simulated in the model. Irrigation demand was supplied primarily from surface water in the Ten Mile Creek. Additional water was needed to supplement the irrigation demand from external sources. The irrigation data of North Fork basin in Table C3-4 referred to the Project water as part of the supplemental irrigation supply.

Comments from Carl Woehlcke

34. Existing conditions and expected future conditions have been moving away from the land-use and land cover assumptions used in the PIR. Historically, during dry periods, water used by citrus was of paramount importance. One pattern is that water would be withdrawn from the canals for irrigation purposes down to a set allowed level (crown flood irrigation). This irrigation method tends to tie up a large amount of water in the application process. A second aspect of citrus irrigation was that during dry periods, Florida aquifer wells would be allowed to flow bringing additional, brackish, water to the surface water system. Citrus disease and competition with urban land uses, indicate that the continuation of this pattern into the future is not likely and could have a number of effects on water use and run-off especially during the dry season. Less Floridan aquifer water may be brought to the surface, however, evapotranspiration of replacement land uses may well be less than that of citrus and water table levels may not need to be maintained.

    The land-uses most likely to replace the citrus is urban, and additional development is expected along the North Fork. Not only will urbanization effect runoff characteristics, but, because the water used by utilities in St. Lucie County is almost all brackish Floridan water, virtually all of this water will be used for irrigation purposes (either directly or as reclaimed water), this may well have a significant impact on the amount and timing of water going to tide, during the dry season. Have these considerations have been taken into account in your analysis?

    Section 4.7.3.3 addresses many of the concerns regarding expected changes in water demands and sources of potable and irrigation water. Also, as described in Section 9.2, the rule will be evaluated and updated periodically to respond to changing conditions. Rule creation does not alter existing legal uses of water so long as they are not contrary to the public interest.

35. The primary problem in the IRL system is the delivery of excessive water to tide. A significant portion of IRL project expenditures are associated with the purchase and rehydration of lands within the basin. A major benefit cited for this rehydration is the increase in evapotranspiration and hence reduction in runoff. The District is constrained by state/federal agreements to provide assurances that water in the CERP plan to be used for environmental purposes will be there when it is needed. In the technical document, it is shown that significant additional water is moved to the North Fork to help maintain flows. It is not clear that if there is need for water is to increment those flows, that this water might not be made available from the project by changing assumed operating criteria.

    The hydrological benefit of the rehydrated lands under the future with project condition (Table 7.1) is simulated by the watershed model, which takes into account of the wetland hydrology. The flows diverted into the North Fork are mostly harmful watershed runoff, which would otherwise be lost to tide. While the operating criteria will be a key factor in determining the water availability. However, the general operational rule of the C-24 Stormwater Treatment Area is to provide continuous water quality improvement and flow delivery into Ten Mile Creek when there is water in the reservoirs while the C-23/C-24 Reservoirs will be operated in a way to be close to the full capacity before the onset of the dry season.

36. Questions were raised about boundary conditions, as it relates to maintaining areas of low salinity. At the south end of the target area for maintaining low salinity is the outlet to tide from the C-24 canal. It would seem that outflows from C-24 might also have a significant effect on the salinity upstream, especially if those releases occurred during incoming tides so that the released freshwater would move upstream. The first point above indicates that there might be additional flows to tide from urbanized areas during the dry seasons related to lower evapotranspiration in urban areas, and to the additional water brought to the surface water system from the Floridan aquifer.

    The boundary condition for flows from C-24, C-23, and C-44 was assumed to be 120 cfs for the development of the mean monthly flow target (130 cfs over the Gordy Road Structure). The 120 cfs flow is considered to be representative of the typical dry condition in the area. If a storm event occurs in the dry season, flows over 120 cfs may be delivered to the system from these canals and the nearby urban area. These events are episodic, and are normally rare in the dry season. Refer to comment #20 and the authors' response for further information regarding the separation of the Floridan and surficial aquifers.

37. There is a weakness in the frequency distribution curve approach. I believe that the salinity effects on the environment relate to a very short timescale. Since the frequency distribution curve reflects an evaluated result, over a multiyear period would it not ignore variations in the number of years and the time periods within each year when the flows fall short of the target?

    It is true that the temporal variation of salinity in the system can be characterized at annual, seasonal, monthly, daily, or evenly hourly scales. Ecosystem response to these variations can also be evaluated accordingly. The authors fully realize the importance of the variability and that is why we used the pulsed flow concept to maintain a dynamic distribution of the 1 psu isohaline between Prima Vista Bridge and Kelstadt Bridge. Besides the frequency distribution curves as one way to evaluate the results, we also examined the monthly flow time series (Figure 7.7) to demonstrate the months and the years when the target flow were not met during the 41-year period of record. The purpose of Figure 7.8 is to demonstrate, from a spatial perspective, that the project will be able to greatly improve the salinity habitat in North Fork to maintain a dynamic distribution of the 1 psu isohaline between Prima Vista Bridge and Kelstadt Bridge.

Comments from USFWS

38. Figure 7-2; Pages 7-6 and following pages. Discussion at the workshop indicated there is scientific uncertainty about the ecological response to pulsed flows. Given that operations will be adjusted in response to actual project performance, it would be valuable to confirm that the volume of water being proposed for the reservation is not dependent on the specific operations assumed in the modeling. We suggest an additional simulation be run that assumes a constant dry season flow of 130 cfs. This would provide a check that the flows proposed for the reservation are sufficient to move the oligohaline zone downstream with or without pulsed operations.

    As stated in Section 5.1.3.2 pulse release flows were used as the basis to define the performance measure (the 1 psu isohaline and its movement) that was in turn used to determine the hydrologic target. The hydrodynamic modeling applied to determine the location of the 1 psu isohaline and its movement within the North Fork (Sections 7.22 and 7.23) as well as ecologic considerations (see Section 6 and Section 5.1.3.1) clearly establish flow pulses that mimic natural patterns will be needed to reach the desired location and create the desired physical and biological characteristics of the estuarine turbidity maximum. Maintaining a constant flow of 130 cfs is not proposed as part of the water reservation rule. The operational protocols associated with the water reservation rule are recognized as a source of uncertainty (Section 7.5.1) and monitoring will be addressed as part of the final detailed project design (See Section 7.6). Because the details associated with delivery of pulsed flows are operational issues, they are not addressed as part of this technical documentation (see also comment #5). Monitoring, development of an adaptive assessment plan, and future rule updates will provide the needed "check" that the water reservation provides sufficient flows to protect fish and wildlife. See also responses to comments #6, 12, 19, 27, and 30.

39. Salinity Tolerances of Species. The peer review panel suggested the report include additional information on the salinity tolerances of species in the SLE. Consider incorporating the information contained in the SFNRC Technical Series 2006: "Ecological and Hydrologic Targets for Western Biscayne National Park, which compiles and synthesizes information on the salinity requirements for several species, including spotted seatrout, mojarra, silver perch, and eastern oyster.

    The District appreciates the direction to the SFNRC document which proposes "optimum" salinity ranges for a number of estuarine species found in Biscayne Bay. Except for two, the majority of species identified require optimum salinities > 10 psu, which is outside the 0-10 psu range that characterizes the North Fork of the St. Lucie River. Of the two, juvenile crocodiles are not present within the St. Lucie estuary and widgeon grass is sparse. Additionally, the authors' technical approach focused on defining salinity tolerance information that could be used to identify potential valued ecosystem component species, which is a slightly different process than defining optimum salinity conditions. Although this information is helpful in managing resources present within the downstream estuary, for the reasons discussed above, this information was not used as a method for valued ecosystem component selection within the North Fork of the St. Lucie River.

40. The review panel suggested that the available Habitat Suitability Indices (HSIs) be consulted for additional biological information that may add scientific support for the Water Reservation. The HSIs are available at http://www.nwrc.usgs.gov/wdb/pub/hsi/hsiindex_bynumber.htm.

    The District appreciates the direction to this valuable resource. Our review of the HSI's listed on this site showed only four (HSI's for oysters, larval and juvenile red drum, spotted sea trout, and pink shrimp) that might potentially apply for the North Fork of the St. Lucie River. More detailed review of this information showed that these HSI's could not be directly applied to the low salinity conditions that represent the North Fork of the St. Lucie River.

41. Figures 8.1 and 8.3. These volume probability curves illustrate the without project, with project, and target flows into the North Fork and measured at Gordy Road. In both figures the blue trace showing the target has a break point at approximately the 90th percentile, above which the line drops quickly from 130 cfs to less than 50 cfs, then to zero. This differs from the way targets have been defined in other technical reports used to quantify water for fish and wildlife and restoration (e.g., for the Picayune Strand and Kissimmee River/UCOL technical reports). If the ecological rationale is that 130 cfs is the "amount of fresh water needed to be delivered by the Ten Mile Creek (Gordy Road Structure) during the dry season to protect larval and juvenile fish habitat within the North Fork then the target trace of 130 cfs should continue out to the 100th percentile of the volume probability curve, regardless of whether or not water is available during all portions of the dry season. We suggest that the target trace of 130 cfs be extended to the 100th percentile. This would not affect the quantification of water to be reserved, as that would be the lesser of either the target or the actual delivery from the project. However, it would avoid inconsistency with previous applications of volume-probability curves, and prevent the mistaken interpretation that very low (even zero) mean monthly flows are desirable "targets."

    District staff agrees with this comment and has revised the volume probability curves shown in Sections 8 and 9 of this report.

42. Adaptive Management. The peer review panel discussed the need for adaptive management to assess and improve the response of the oligohaline zone to the project's flow regime. The water reservation is only a component of the overall implementation of the IRL-S Project. A monitoring and assessment plan is in place for flow and water quality in the St. Lucie River and Estuary system. In the future, there will be additional periodic opportunities to address the efficacy of the monitoring and assessment plan.

The District agrees that monitoring will be part of adaptive management. Monitoring will be addressed in the operations plan as part of the detailed project design. For further information, see general discussion added in Section 7.6 and responses to comments #6, 12, 19, 27, 30, and 38.

References:

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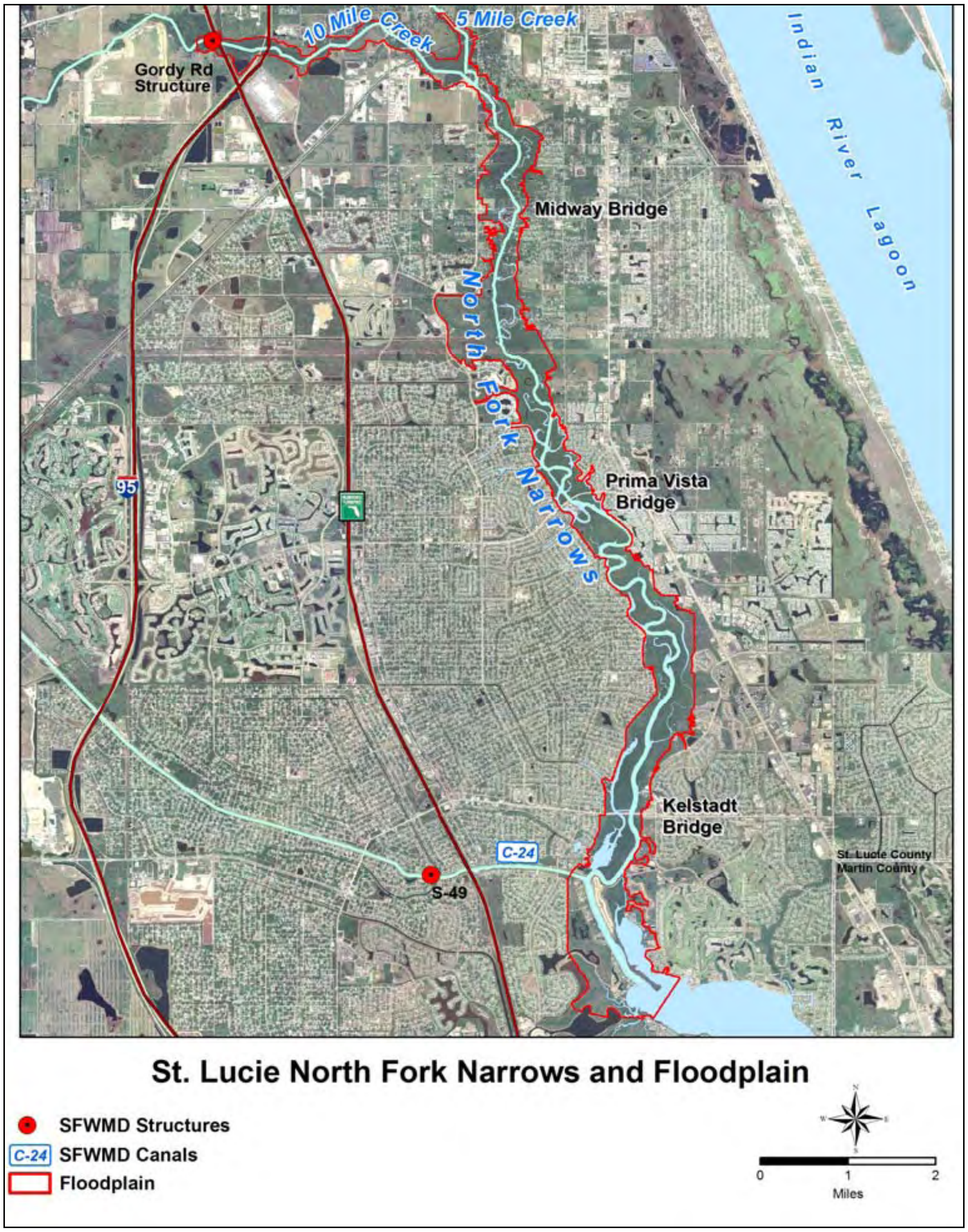
Appendix B.
The Methodology of Creating a Seamless DEM of the St. Lucie North Fork Narrows and Its Floodplain

Elevation data is an important component for understanding the hydrology and hydrodynamics of the North Fork of the St. Lucie. The North Fork is a major tributary to the St. Lucie Estuary and is tidally influenced to its upstream headwaters, Ten Mile Creek and Five Mile Creek. The North Fork Narrows, as its name implies, is the narrow section of the North Fork and measures approximately 14 miles in length. A tool to better understand this portion of the river and its floodplain, is a digital elevation model (DEM). The DEM can be analyzed for floodplain inundation, storage capabilities, and restoration areas. It can also be used as input to the various models.



Elevation Data

Three bathymetry datasets have been collected in the North Fork Narrows since 1998. Morgan and Eklund surveyed a small portion of the Narrows in 1998, the USGS surveyed the entire North Fork in 2003, and a private contractor collected bathymetry for the entire North Fork Narrows in 2006.

In 2007, terrestrial LiDAR was flown over the North Fork Narrow's floodplain. Due to the dense vegetation of the area, the LiDAR was collected using a helicopter, which could fly much lower and collect a higher point density with a higher degree of accuracy than a fixed wing aircraft. The helicopter flew in multiple directions over the same area to penetrate the tree canopy from different angles with the LiDAR sensor. The specification for the vertical accuracy of the LiDAR was to meet the accuracy standards for 2-ft contours in the vegetated areas.

To support 2-ft contours, according to FEMA mapping standards, the root mean square error (RMSE) of the data must be 0.61 ft. or less. The LiDAR for the floodplain exceeded these specifications with a RMSE of 0.14 ft.

The following table lists the specifications for each bathymetry dataset:

Contractor	Area	Year	Vertical Datum Collected	Accuracy
Morgan and Eklund	Southern End of the North Fork Narrows ending upstream at the Keldstadt Bridge	1998	NGVD29	.3 ft.
USGS	North Fork Narrows beginning at Keldstadt Bridge	2003	NAVD88	4 cm
Steve Van Meter Consulting	Entire North Fork Narrows	2006	NGVD29	NA

Methodology

Using the tools in ESRI's ArcGIS, the bathymetry datasets were converted to the vertical datum, NGVD, and units of feet as needed, then merged into a single point shapefile.

Due to the limitations of echo sounders and the shallow waters restricting the operation of the survey boat, bathymetry is lacking at or near the shoreline. A uniform elevation was established at the shoreline by analyzing several years of data from three stage recorders on the North Fork Narrows (**Figure 1**). The average stage at the three sites differed by only 0.16 ft, which was less than the stated accuracy of one of the bathymetry datasets (0.3 ft). and almost equal to the accuracy stated for the LiDAR. It was then determined to use the average value from the three stage recorders, 0.74 ft, as the elevation value at the shoreline for the entire North Fork Narrows.

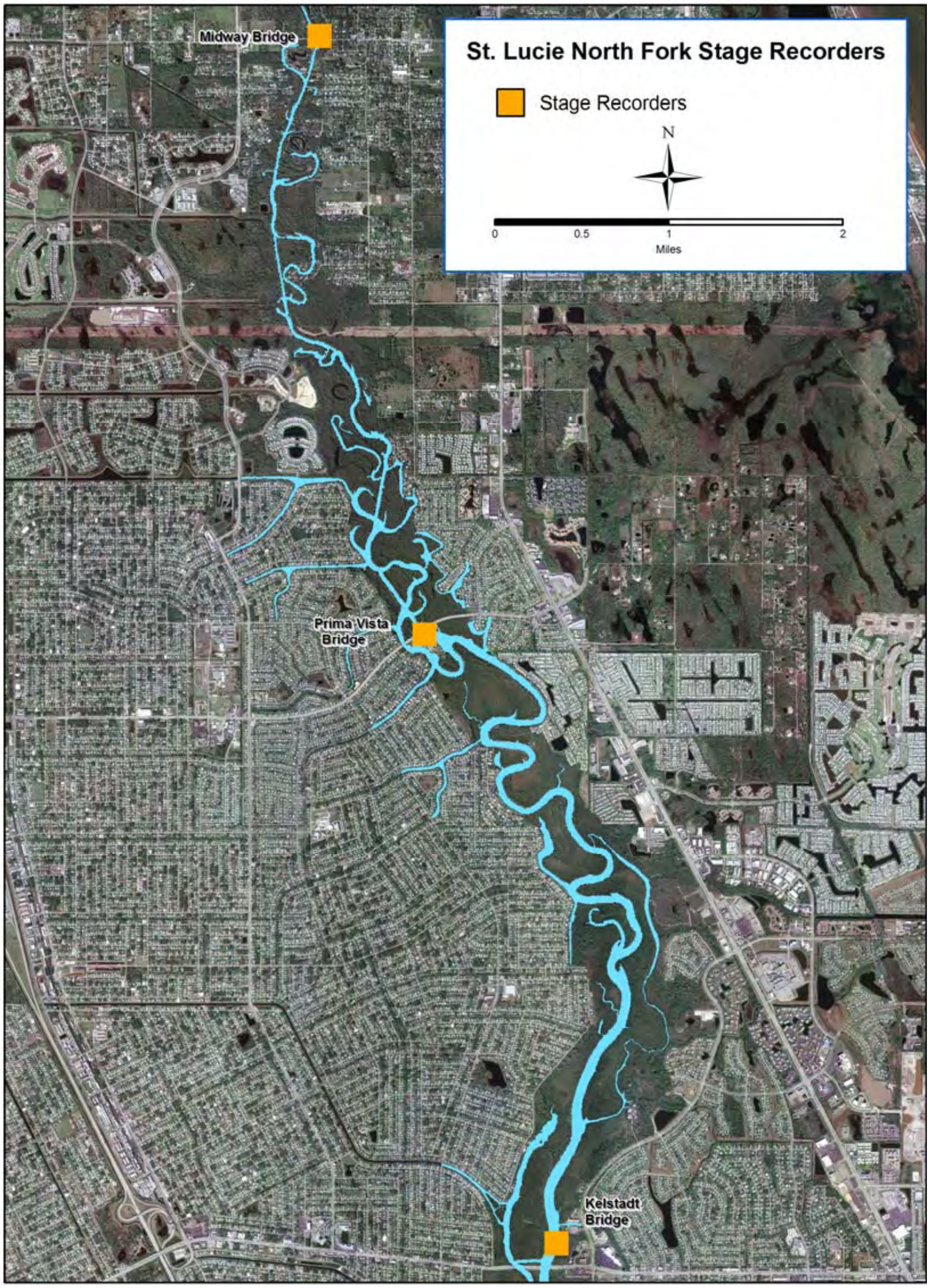


Figure 1.

After all of the input data was ready for the interpolation process, the first step in creating the DEM was producing a triangular irregular network (TIN) for the area of the river. A TIN is a vector-based representation of land surface, in this case the bed of the river channel. It consists of irregular, non-overlapping triangles. The advantage of using the TIN interpolation is the nodes of the triangles keep the original value of the input data. It is only between the nodes where the interpolation is done (**Figure 2**).

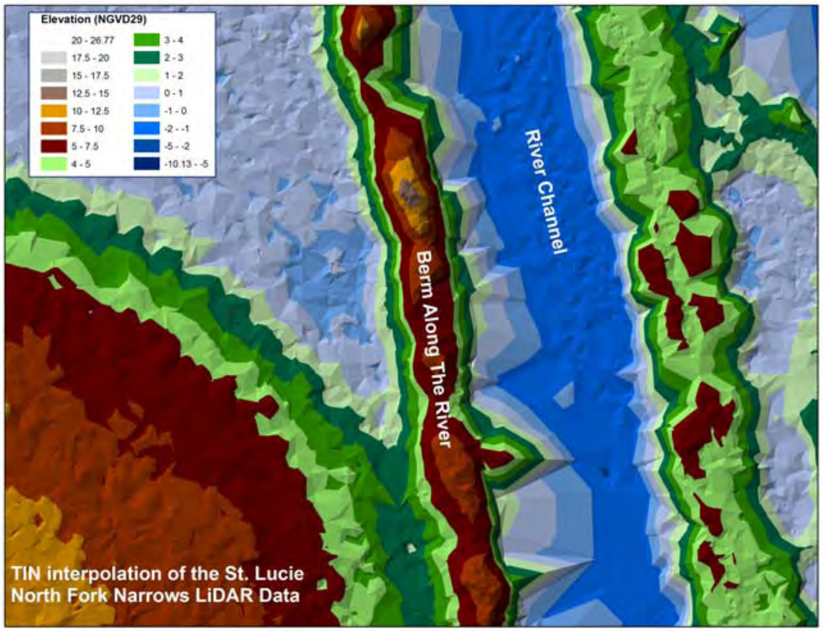


Figure 2. This is an example of a TIN. Note the irregular triangles. This TIN was created from the LiDAR data only. The bathymetry data was not included in the interpolation. One can clearly see the berm to the left of the river channel.

The initial North Fork Narrows bathymetry TIN was an interpolation of the bathymetry point data, and the mean stage of 0.74 ft. along the shoreline.

In areas of numerous and randomly spaced bathymetry points the TIN produced a good representation of the river's bed. However, in areas lacking data or in areas of bathymetry in cross sections, the TIN misrepresented the river bed by creating artificial interpolation artifacts. Most of the interpolation methods in ArcGIS do not consider the direction of the river's course but interpolate in a more homogenous way in all directions. To mitigate this issue, contours were created from the initial TIN, edited to follow the course of the river and added to the interpolation process. This forces the interpolation to follow the course of the river (**Figures 3 and 4**).

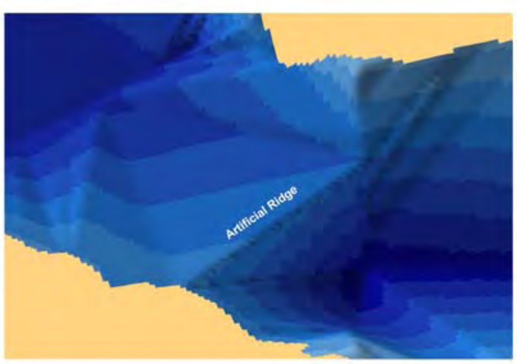


Figure 3. The initial TIN of the bathymetry created this artificial ridge in the river's bed where there was a lack of bathymetry data

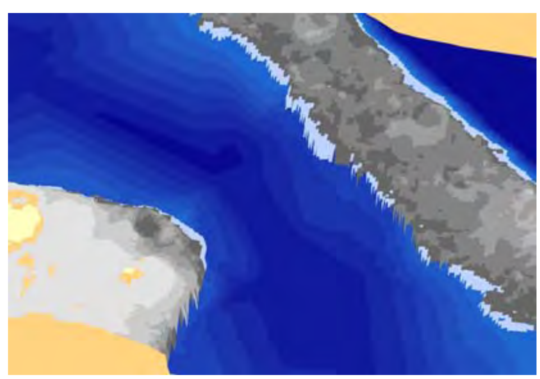


Figure 4. The artificial ridge has been removed by editing the contour lines and using them in the interpolation process. This figure also includes the LiDAR data.

The second step in creating the DEM was producing a TIN from the floodplain's LiDAR data. Since the LiDAR is a high-density point dataset (**Figure 5**)**,** the LiDAR was divided into four different datasets. Each dataset overlapped the other by no less than 800 feet to facilitate their seamless merging.

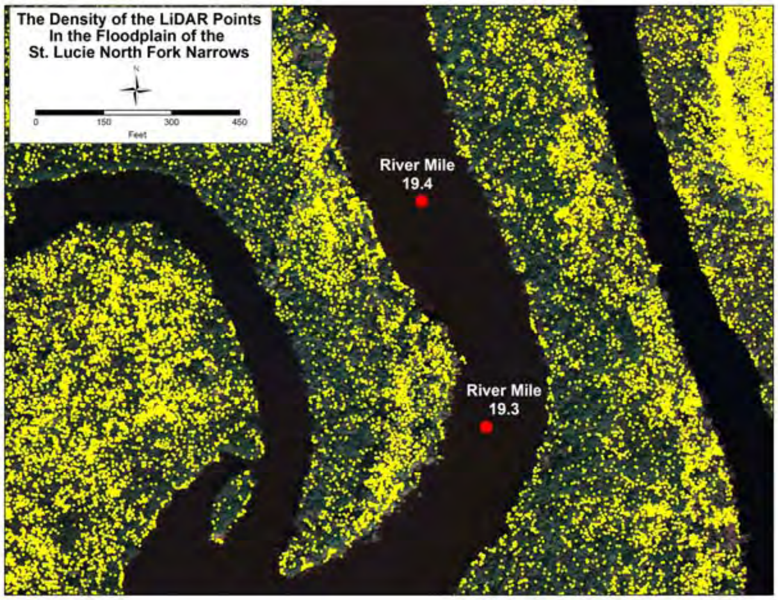


Figure 5. This is a typical density of the LiDAR points in the floodplain of the St. Lucie North Fork Narrows' floodplain.

The TINS produced for each LiDAR subset were converted to ESRI grids (raster datasets) with a 5-foot pixel resolution and merged into one grid for the North Fork Narrows Floodplain. Likewise, the TIN for the North Fork Narrows bathymetry was converted to a 5-foot resolution ESRI grid.

Finally, the LiDAR and the bathymetry grids were merged into a seamless DEM for the entire St. Lucie North Fork Narrows and its floodplain (**Figure 6 and Figure 7**).
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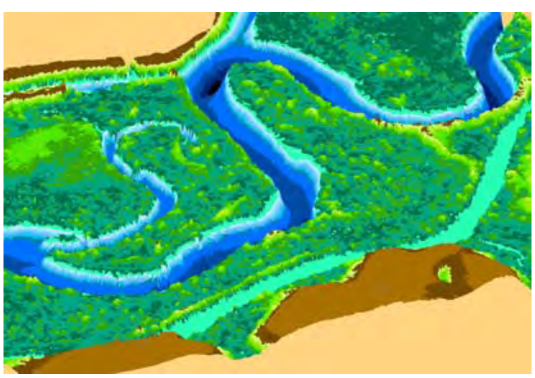


Figure 6. A look at a portion of the final DEM in 3D

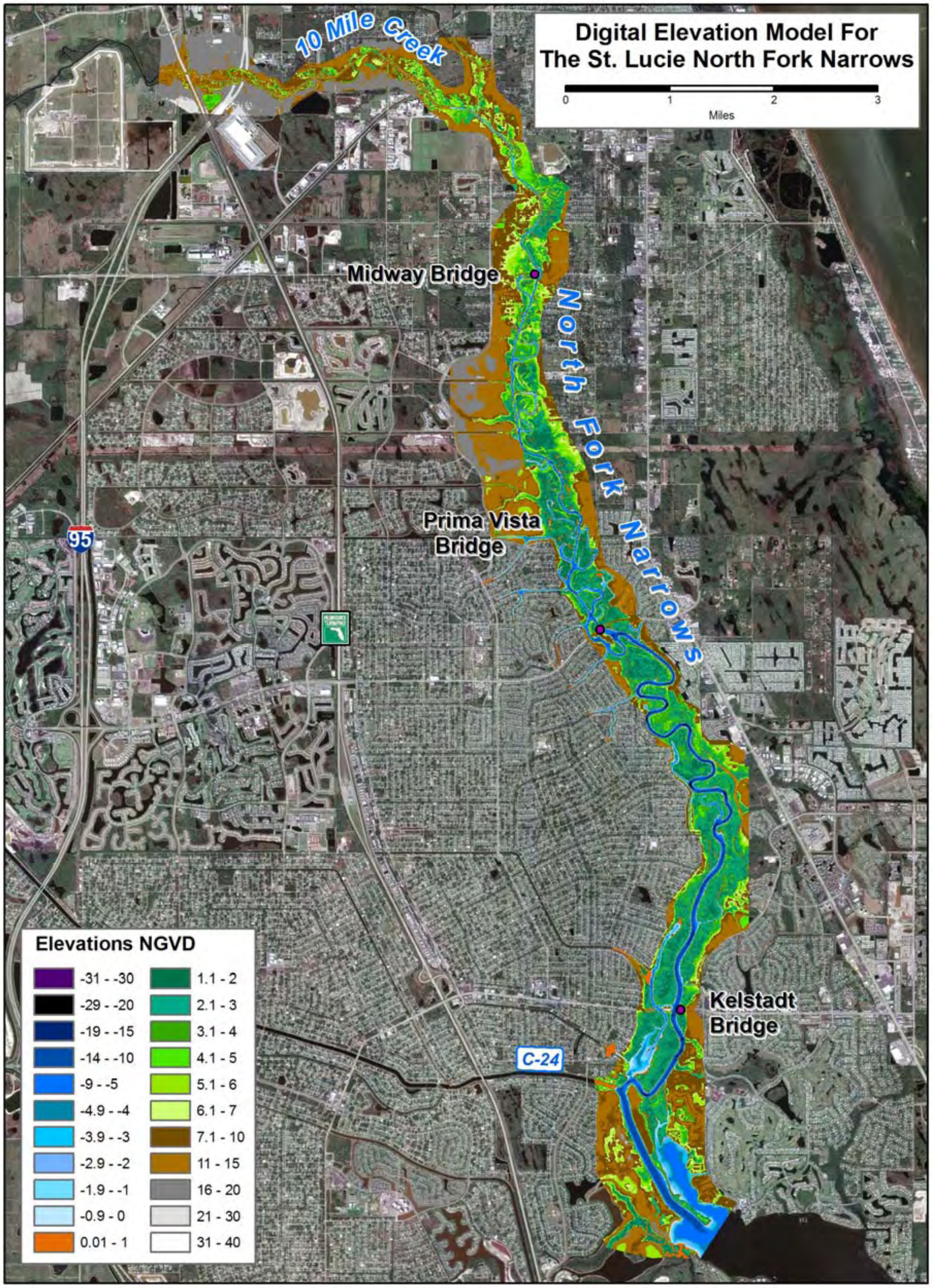


Figure 7. The final digital elevation model for the North Fork Narrows

Analyzing the DEM for Floodplain Inundation

The final North Fork Narrows DEM was analyzed using ArcGIS to determine the inundation of the floodplain at four different stages of the river, 1 foot, 1.5 feet, 2 feet and 2.5 feet. The goal of this analysis was to establish the river stage beneficial to connecting the river's main channel to the floodplain for fish habitat and restoring a healthy hydrology for the wetland communities.

The area of inundation was calculated for all four stages as shown in the table below:

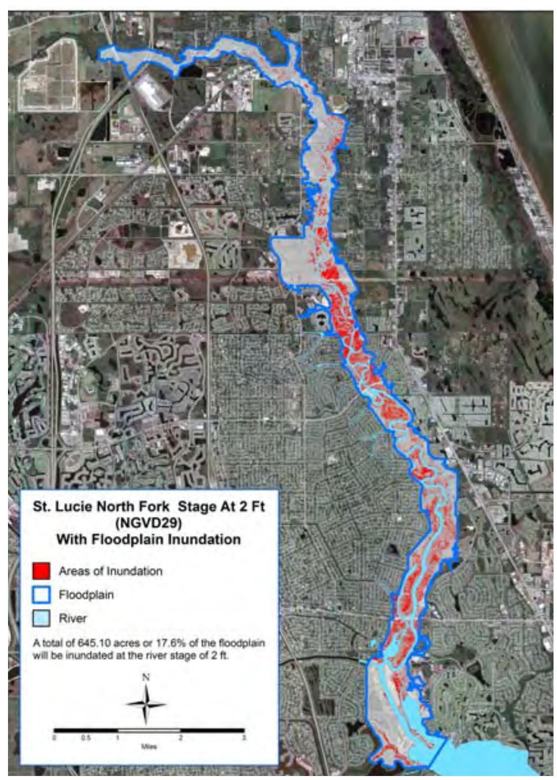
St. Lucie North Fork Stage and Floodplain Inundation

Stage of River (NGVD29)	Floodplain Inundation (Acres)	Floodplain Not Inundated (Acres)	Percent Inundated
1.0 Ft.	84.73	3581.19	2.31%
1.5 Ft.	269.94	3395.99	7.36%
2.0 Ft.	645.10	3020.83	17.60%
2.5 Ft.	1027.56	2638.36	28.03%

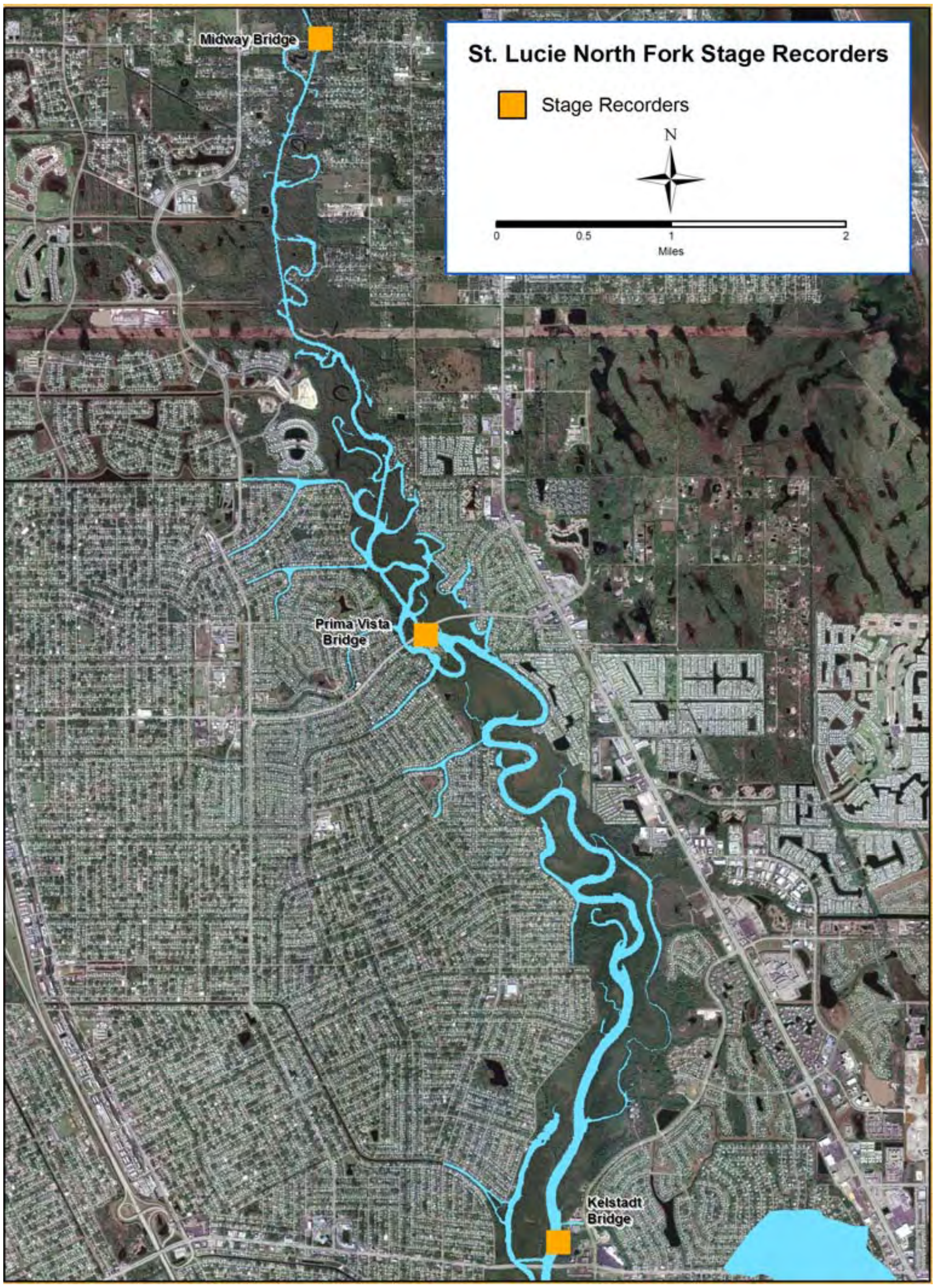
*Total Area of the Floodplain is 3665.92 Acres

The results of the analysis showed the river must reach a stage of approximately 2 feet for significant floodplain inundation. The duration of the inundation is integral for the fish habitat because the floodplain needs to remain connected to the main channel. This inundation and connectivity provides a nursery area for larval and juvenile fish.

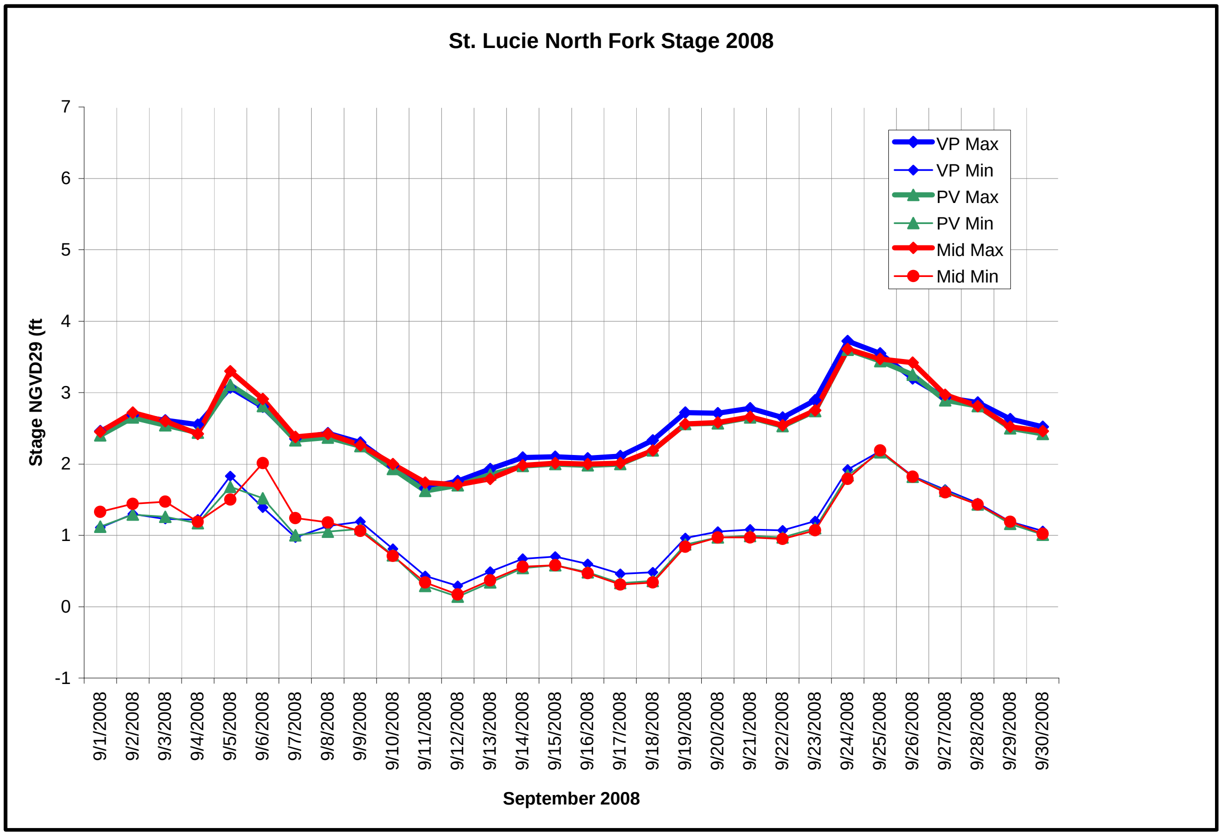
Duration of floodplain inundation is important to the wetland vegetation communities but unlike fish habitat, these communities do not need the connectivity to the river's main channel. It is assumed the wetland vegetation would derive some benefit from a short period of inundation. This, however, will need to be further studied.



Along with the DEM analysis, the stage data of the river was analyzed to determine the stages of the river and duration for the period of record. The river stages have been monitored at three locations. Traveling upstream, the sites are Veteran's Park just north of the Kelstadt Bridge, Prima Vista Bridge, and Midway Bridge.



River stage has been monitored at these sites since November 2002 with a break in the monitoring occurring after the 2004 hurricanes. The monitoring resumed in May 2006 and has continued to the present. The daily minimum and maximum stages were analyzed at each site. There was not a great deal of difference between the stages at the 3 different sites as seen in the following graph. When applying the different river stages in the DEM analysis, it was decided that the same stage could be applied throughout the St. Lucie North Fork Narrows and its floodplain.



Historically, September is the wettest month of the year. The September stage data was analyzed and it was noted that the average minimum stage for all the years fell below 2 feet. Usually, only during a major storm was the stage above 2 feet, as seen on September 4 to 5 during Hurricane Frances. The minimum stage during Hurricane Frances was 2.86 at Veteran's Park. Nevertheless, looking at the average maximum stage for September, it was 2 feet or more for every year except 2006. Listed in the table below are the stage data averages for the month of September for all of the years recorded.

Stage Data September Minimum and Maximum Averages						
	VP Min	VP Max	PV Min	PV Max	Mid Min	Mid Max
2003	0.58	2.11	0.44	2.01	0.49	2.06
2004	0.97	2.49	1.13	2.57	1.32	2.78
2006	0.29	1.75	0.07	1.64	0.04	1.65
2007	0.71	2.24	0.59	2.16	0.69	2.21
2008	1.10	2.55	1.03	2.47	1.07	2.51

In conclusion, the river, as it is managed today, can reach a stage for floodplain inundation but not for any significant duration. Due to the lack of duration, fish habitat does not extend into the floodplain. It is assumed that wetland communities would benefit from this type of inundation.

Appendix C
Modeling Freshwater Inflows into the St. Lucie Estuary Using the WaSh and OPTI6 Models

YONGSHAN WAN AND FAWEN ZHENG

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C1. INTRODUCTION

The St. Lucie Estuary (SLE), located on the southeast coast of Florida, is the largest tributary to the southern Indian River Lagoon (IRL), which has been considered one of the most biologically diverse ecosystems in North America (Swain et al., 1995). Freshwater inflows into the estuary are the single most important determinant of estuary health. Historically, the watershed draining into the estuary supported extensive areas of ridges, sloughs, pine flatwoods, upland scrub, wetland flats, cypress ponds, and savannas. Drainage of these areas was afforded by wetland systems flow into two major meandering streams, namely North Fork and South Fork, and percolation into groundwater. Waters thus entered the estuary relatively slowly and contained little nutrients.

Over the last 100 years, land use and drainage patterns in the watersheds have undergone substantial changes as a result of the construction of a network of primary, secondary, and tertiary canals. The large primary South Florida Water Management District (SFWMD) canals C-44 (completed 1924 and enlarged to its current size in 1949) and C-23, and C-24 canals (completed circa 1961), were constructed by the U.S. Army Corps of Engineers (USACOE) under the auspices of the original Central and South Florida Project. These canals drained many historic wetlands, and allowed widespread agricultural and urban development of the watershed. As a result, the quantity, quality, timing and distribution of the freshwater inflows have been significantly altered, inserting major influence on the overall estuary productivity and health. The present freshwater flow pattern has been characterized as the follows:

1. The exaggerated low flows during the dry season months;
2. The reduction or lack of flush from spring rainfall due to irrigation for agricultural activities,
3. An excess quantity of fresh water received during the wet season for crop and residential flood protection,

To address these issues, the SFWMD and the USACOE teamed up to develop a restoration plan aiming to re-establish an appropriate salinity regime and improve water-quality conditions in the estuary through construction of large regional reservoirs and stormwater treatment areas (STAs), as well as rehydration of large tracts of former wetlands through the Comprehensive Everglades Restoration Plan (USACOE and SFWMD, 2001). A suite of models dealing with watershed hydrology, reservoir optimization, estuary salinity and ecology are applied for optimal sizing and operation of stormwater reservoirs (Wan et al., 2002). This integrated model approach is continued in the St. Lucie River Watershed Protection Plan under the Northern Everglades Program, and now in the Water Reservation project. In this effort, a watershed model (WaSh) was used to simulate the watershed hydrology of the project base conditions and a genetic algorithm based optimization model (OPTI6) was used to generate the capacity and operational rules that govern water release to the SLE. A 41-year period of record (POR) consisting of daily freshwater flows into the estuary was simulated to ensure that a wide range of climatic conditions was included. The purpose of this document is to provide the technical details of how the St. Lucie Estuary Watershed Model (WaSh) and the Optimization Model (OPTI6) were developed and applied in the St. Lucie River Watershed Protection Plan and the Water Reservation Project (**Figure C1-1**).

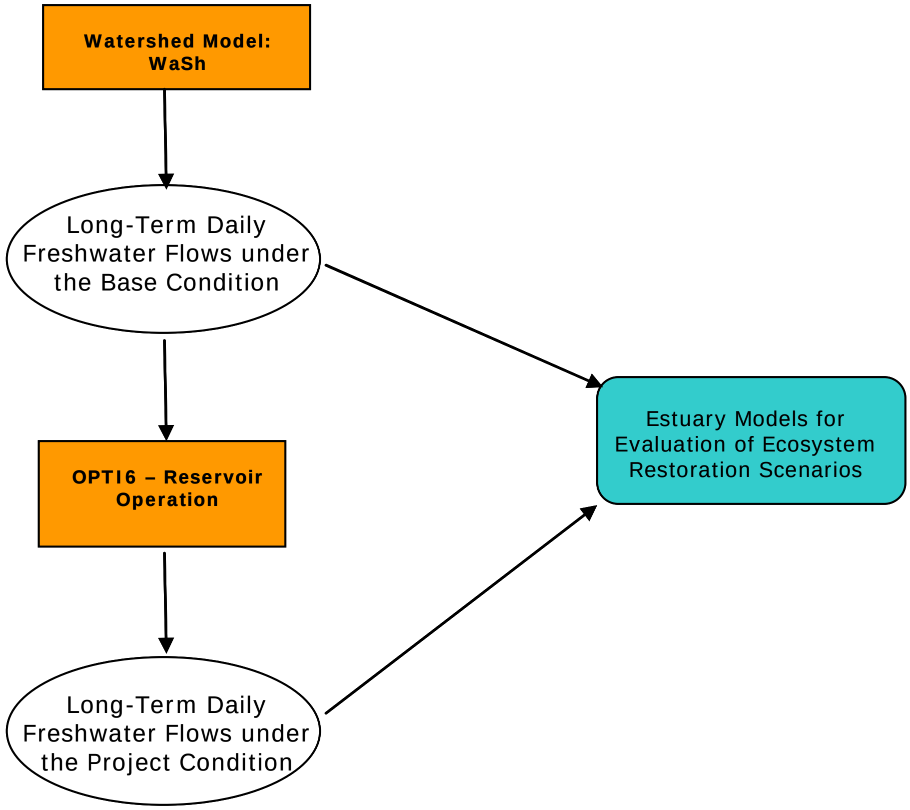


Figure C1-1. The applications of the SLE WaSh Model and the OPTI6 Model for ecosystem restoration.

C2. SIMULATING WATERSHED HYDROLOGY USING WASH

WASH MODEL DESCRIPTION

During the past decades, the South Florida Water Management District (SFWMD) has initiated several modeling projects to simulate freshwater inflows into the St. Lucie Estuary. Watershed modeling started in 1994 when the SFWMD contracted Aqua Terra Consultants to modify the Hydrological Simulation Program Fortran (HSPF) model for southern Florida hydrology. The project was completed in 1998 with the generation of the newest version of HSPF (version 12). The model was implemented in the SLE watershed including North Fork basin, South Fork basin, C-24 basin, C-23 basin, C-44 basin, and basins of 4, 5, and 6. The modeling result was used in the Southern IRL Feasibility study (Wan et. al. 2002; Wan et. al. 2006).

In order to model watershed water quality and overcome the shortcoming of the lumped nature of HSPF, the SFWMD initiated another project in 1999 to develop the **Wa**ter**sh**ed Water Quality Model (WaSh). The WaSh model was developed based on restructuring the HSPF (Hydrologic Simulation Program – Fortran, Donigian, 1984) into a cell-based system with the addition of a groundwater model and a full dynamic channel routing model (Wan et al. 2003; URS, 2003). The model is capable of simulating hydrology in watersheds with high groundwater tables and dense drainage canal networks, which is typical in South Florida. The model consists of four basic components: (1) a cell-based representation of the watershed basin land surface, (2) a groundwater component that is consistent with the basin cell structure, (3) a surface water drainage system, and (4) water management practices. Key features of the model are surface water and groundwater interactions, irrigation demands, and transfers between elements of the surface water drainage network. For each cell, the model uses an infiltration routine to determine the amount of rainfall that infiltrates into the groundwater, evaporates into the atmosphere, or drains to the surface water system. The HSPF (Version 12) modules PWATER and IWATER are used for this portion of the model. The infiltrated water is routed to a groundwater model that represents the unconfined aquifer in the watershed. The groundwater model receives the infiltrated water, exchanges groundwater between cells, and also exchanges water between surface water flow and groundwater flow. The surface water drainage system consists of a cell-based system and a reach-based system. The reach-based system is typically configured to follow the major canals, streams, and rivers and supports branches and common flow control structures. The WaSh model is supported by a Graphic User Interface (GUI), which handles file management, model configuration, execution, and model input data pre-processing. Key components of the WaSh model are summarized in **Table C2-1**.

Table C2-1. The Watershed (WaSh) Model Components and Functions.

Model Component	Modeling Approach	Functions
Surface Water Flow	PWATER and IWATER of HSPF	Simulation of ET, Interception, Infiltration, Surface Water Runoff, Soil Water Storage, Percolation with High water table algorithms of HSPF
Groundwater Flow	A 2-D unconfined groundwater flow model	Simulation of Unconfined Groundwater Flow Movement, Water exchange between Groundwater and Canal Flow
Channel Flow	A 1-D fully dynamic shallow wave model	Simulation of Canal Network Flow Routing and Flow Control Structure Operation,
Water Management	Reservoirs, Stormwater Treatment Areas, irrigation supply and demands, land use changes	Simulation of Water Movement in Reservoir and STA, Irrigation, and Application of BMPs.

Model Cell Structure and Cell-based Routing

The WaSh model uses a uniform structured grid network. Each cell represents a discrete part of the model domain and has associated physical characteristics such as land use, soil type, ground elevation, impervious area, and a representative ground slope. Hydrological parameters relating runoff, infiltration, and evaporation are specific to these attributes, particularly land use types. For example, swamps and forests have different model parameters so that their hydrologic responses to climatic input can be properly simulated. If tertiary canals are present in the cell, then the total length of canals in the cell are computed and added as a cell attribute. Generally, the cell attributes are obtained by combining the cell network with Geographic Information System (GIS) coverage for each of the physical characteristics. For the purpose of routing the simulated daily runoff from each cell, a special cell attribute is assigned to indicate where runoff from that cell is directed. Each cell is labeled as one of four primary types: (1) free cell, (2) canal cell, (3) reach cell, or (4) reservoir cell. A free cell represents an area of the basin that does not contain canals. Canal cells are any cells with tertiary canals that are not coincident with the reaches (primary canals). Reach cells are the cells that contain a reach of the primary canal system. Some secondary canals can be included in the reach system. Reservoir cells are the cells representing a reservoir in the landscape. There can also be hybrid cells among the four to represent the interactions. These labels are needed to designate the types of surface water and groundwater interactions that may occur for a given cell. **Table C2-2** lists the methods in which water is routed for each type of the major cells.

Table C2-2. WaSh Water Routing Operations for Major Cell Types.

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

Surface Water, Groundwater, and Their Interaction

The surface water and groundwater is modeled in the same grid cell network. For each cell, WaSh uses the PWATER and IWATER modules of HSPF (Version 12) to simulate surface water hydrology (**Table C2-1**). A detailed description of these modules is available in the HSPF user's manual (Donigian et al. 1984). HSPF Version 12 includes recent model enhancements that simulate irrigation demand, high water tables, and wetland conditions that are common in South Florida (Aqua Terra 1996). The HSPF routine is implemented in one-hour time step for 24-hour blocks. Thus, the HSPF-based routine is applied daily for each cell and water balance, consisting of rainfall, evaporation, soil storage, surface runoff, and infiltration to groundwater. At the end of each one-day simulation period, the accumulated surface runoff and infiltration are routed to the drainage and groundwater systems, respectively. All HSPF model parameters are calibrated and assigned to each cell based on the land use and soil type characteristics as additional cell attributes.

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

$$\rho \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} K_x (h - h_c) \frac{\partial h}{\partial x} + \frac{\partial}{\partial y} K_y (h - h_c) \frac{\partial h}{\partial y} + S_i - S_e + S_c + S_r \qquad \text{[C2-1]}$$

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

$$\rho_{i,j}\frac{h_{i,j}^{m+1}-h_{i,j}^{m}}{\Delta t}=K_x\left[\frac{\left(\frac{h_{i,j}^{m}+h_{i+1,j}^{m}}{2}-h_c\right)}{\Delta x}\left(\frac{h_{i+1,j}^{m}-h_{i,j}^{m}}{\Delta x}\right)-\frac{\left(\frac{h_{i,j}^{m}+h_{i-1,j}^{m}}{2}-h_c\right)}{\Delta x}\left(\frac{h_{i,j}^{m}-h_{i-1,j}^{m}}{\Delta x}\right)\right]+ \qquad \text{[C2-2]}$$

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

where Δt is the time step (one day), and Δx and Δy are the grid cell dimensions in x- and y-direction. During each time step the right-hand side of the equation is evaluated based on current time level conditions, and the new water elevation is found by solving for $h_{i,j}^{m+1}$.

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

$$S_{c_{i,j}}^{m}=\frac{\Delta H\ C_c}{A} \qquad \text{[C2-3]}$$

$$S_{r_{i,j}}^{m}=\frac{\Delta H\ C_r}{A} \qquad \text{[C2-4]}$$

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

Irrigation Demand and High Water Table Conditions

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

$$h_{i,\,j} = h_{i,\,j} + \Delta V / \rho \qquad \text{[C2-5]}$$

where ΔV is the volume (expressed as depth) of groundwater irrigation demand or application for the cell calculated by the HSPF irrigation module, and ρ is the aquifer storage coefficient as defined previously in Equation [C2-1].

The high water table module in the HSPF requires certain vertically referenced parameters and variables to allow for exchange of water between storage components when the groundwater level interferes with the upper and lower zone storage (UZS and LZS). For applications in WaSh, the vertical referencing is already completed, as the surface elevation (a cell attribute) and the groundwater elevation h are all referenced to the same datum. Thus, the only required modification is to provide these two variables to the high water table algorithms. The HSPF high water table algorithm then calculates the exchange between the storage zones and the groundwater. The groundwater elevation is updated with Equation [C2-5], where ΔV now represents the exchange between the upper and lower storage zones.

Drainage Canal Network and Canal Routing

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

Flow through the reach-based systems is modeled using the continuity equation, Equation [C2-6], and the depth- and width-averaged shallow water full dynamic wave equation, Equation [C2-7]. The governing equations are:

$$\frac{\partial wh}{\partial t} + \frac{\partial q}{\partial s} = Q_e \qquad \text{[C2-6]}$$

$$\frac{\partial q}{\partial t} + \frac{\partial uq}{\partial s} + \frac{gw}{2}\frac{\partial h^2}{\partial s} = -w\,\tau_b - gwh\,\frac{\partial \eta}{\partial s} \qquad \text{[C2-7]}$$

where q is the flow, u is the width- and depth-average flow velocity, g is the acceleration due to gravity, w is the canal width, h is the water depth (referenced to the canal bed), η is the bed elevation, t is time, and s is distance along the canal. The bottom stress τ_b is based on a Manning's n formulation. Boundary conditions can be one of two types: a specified flow or a specified water elevation. Specified flow conditions are typically used when a flow structure controls the flow out of the system. The water elevation (or head) condition is used when the system drains unobstructed into a receiving water body. The governing equations are solved using a finite volume procedure, with the segment–node system for a single branch equivalent to a finite volume staggered grid approach.

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

$$Q_e = Q_{kp} + Q_{ki} + Q_{r,gw} \qquad \text{[C2-8]}$$

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

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

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

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

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

$$\Delta s = L, \quad and \ w = w_c \qquad [C2\text{-}9]$$

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

$$\Delta s = LC, \quad and \ w = w_c * \frac{L}{LC} \qquad [C2\text{-}10]$$

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

WASH MODEL IMPLEMENTATION

Model Setup and GIS Coverage

The WaSh model was implemented into five primary drainage basins including C-24 basin, C-23 basin, C-44 basin including S-153 basin, North Fork basin, and South Fork basin, and three minor basins including Basins 4 and 5 (Bessey Creek), and Basin 6 (Danforth Creek). **Figure C2-1** shows the model domain. The cell size was 500 ft by 500 ft for the minor basins and 2000 ft by 2000 ft for primary basins. Input GIS data required to generate the model grid include primary and secondary basin boundary coverage, polygon features with basin name attributes, hydrography including streams and canals as line or polyline features, the 2000 base land use coverage, soil coverage, and land surface elevation. Using the ArcView GUI, these GIS data are overlaid to get an aerial extent of the model domain along with cell attributes of land use type, soil, canal length and width, and elevation.

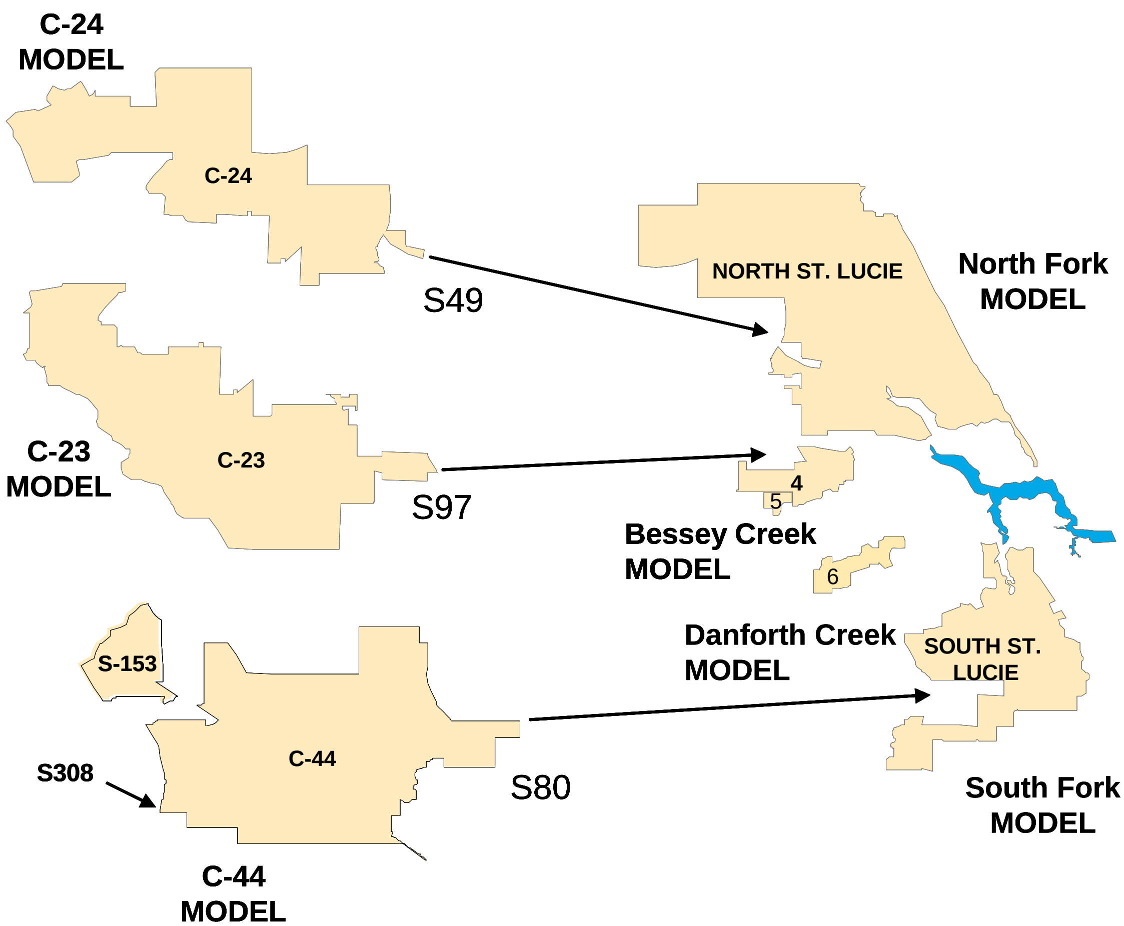


Figure C2-1. The SLE WaSh Model Components and Domains.

The SFWMD Land Use and Land Cover GIS database used for the model input are further aggregated into five general categories for model parameterization:

1. Urban: residential, institutional, commercial, industrial, transportation, open & other;
2. Citrus Groves: citrus groves, cane, truck farms, ornamental, nurseries, tropical fruits;
3. Pasture: improved/unimproved pasture, barren, rangeland;
4. Forest: forest; and
5. Wetland: forested and non-forested wetland .

The Urban category is further divided into sub-categories with varying percentage of impervious areas. The impervious urban land is simulated using the IMPLND module of HSPF, while the pervious urban category is simulated using the PERLND module as Pasture.

Cell Types and Flow Paths

Figure C2-2 show the C-24 model grid as an example which is color coded to represent cell types including free cells (turquoise), canal cells (green), reach cells (pink), and reservoir cells (gray). The surface elevation of cells and the sub-basin delineation were used to create flow paths represented by the arrows in the figure. In general, flow in free cells is routed to the nearest canal or reach cell and flow within a sub-basin is routed to the nearest reaches along the drainage canals.

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

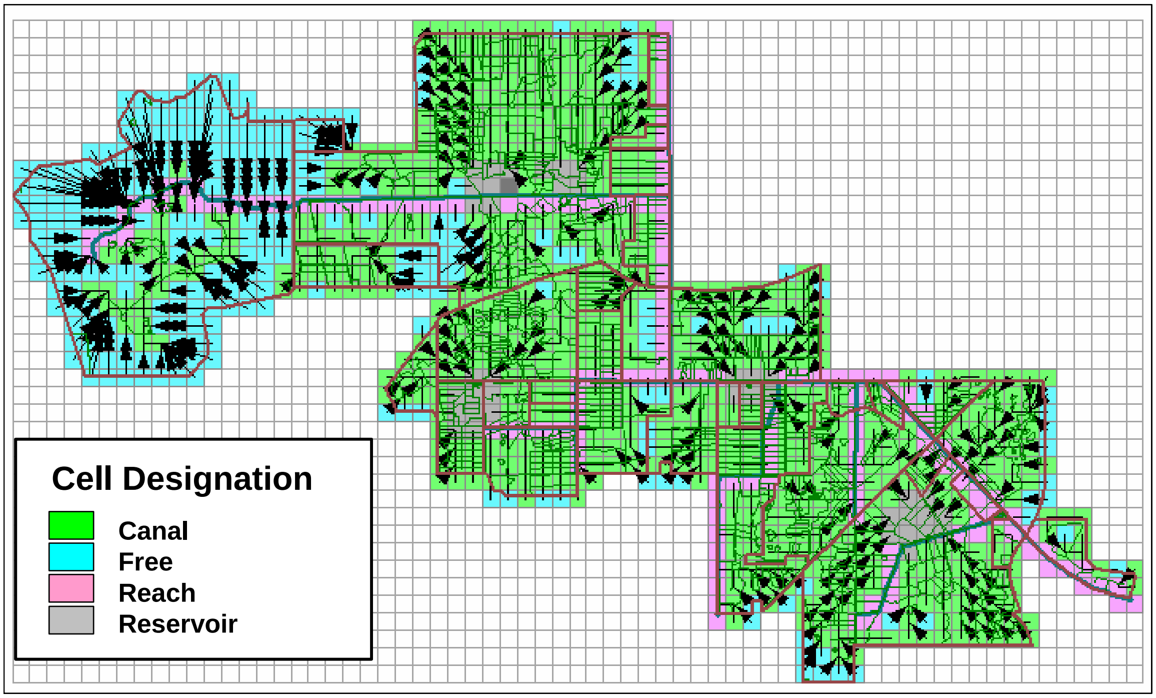


Figure C2-2. The C-24 Model Grid showing cell designation. The green lines represent the hydrography coverage. The red lines represent the sub-basin delineation.

Canal Properties

When creating the primary reaches for the basins, the hydrography theme is overlaid on the grid and those grid cells intersecting with polylines of the hydrography theme are classified as canal cells. The canal length in a grid cell is calculated with all the intersecting canal segments inside a grid cell. Reach cells are created by digitizing major river segments and canals starting from the basin outlet. After digitizing, the length of a reach, which is typically the grid cell size, is specified to allow for redistribution of the nodes along the reach network. Each of the reach segments has a reach ID along with the width and bottom elevation assigned according to the cross-section of the major canal and river segment. The bottom elevation and width of the primary canal reach segments were obtained from cross-sections surveyed by the District. C-24 canal had width that ranged from 80 feet in the headwaters to 200 feet at the S-49 structure. C-23 canal width ranged from 120 feet in the headwaters to 200 feet at the S-48 structure. C-44 Canal width ranged from 250 feet near Lake Okeechobee to 450 feet near the S-80 structure.

Little documentation is available for the width of the tertiary canals and the connectivity. The total length of the tertiary canals in each cell was obtained from the GIS hydrology coverage. The tertiary canal width and bottom elevation depend on the land use and purpose (drainage only or drainage and irrigation). The WaSh model takes an empirical approach to simulate the drainage process by assigning a drainage density and a critical water depth according to the land use types. The critical depth is defined as the depth of water level in the canal to the ground surface so once the critical depth is exceeded, the drainage pump is triggered. **Table C2-3** shows representative properties adopted for the tertiary canals in the watershed. These default values can be changed during model calibration.

Table C2-3. Tertiary Canal Properties for each Land Use Type in the Watershed.

LAND USE	DEPTH (FT)	WIDTH (FT)	DRAINAGE DENSITY (IN/DAY)	CRITICAL DEPTH (FT)
Citrus Groves	10	6	4	3
Pasture	8	4	0.25	2
Wetland	3	2	0.1	0.5
Urban	15	6	14	3
Forest	4	2	0.5	1

Flow Structures

Five structures were explicitly represented in the WaSh models. The structures are the gates at the outfalls of the C-24, C-23 and C-44 canals (S-49, S-48, and S-80) and the Gordy Road Structure. These structures were explicitly represented in the models and the published operational criteria were used to configure the gate model parameters. However, the actual gates are not always operated strictly following the published criteria and adjustments are made manually to their operation in anticipation of large rainfall events and projected draughts. These types for gate operations cannot be modeled accurately and therefore their effect must be considered in the interpretation of the calibration and validation results. Also, the WaSh model representation of gated structure operations does not include all operational controls, and therefore it is necessary to adjust the WaSh model implementation of the structures during the flow calibration to best represent their role in controlling discharges.

Rainfall and ET Data

The most important input data required by the model are rainfall and ET. These data were obtained from the District's South Florida Water Management Model (SFWMM) for the period from 1965 to 2000 (SFWMD, 1998). The dataset was extended to 2005 with available rainfall and ET data stored in the District's DBHYDRO database in the model area. Daily rainfall is disaggregated into hourly rainfall based on an analysis of available hourly rainfall distribution in South Florida.

MODEL CALIBRATION AND VALIDATION

Model calibration involves conducting a model simulation for a selected time and comparing the simulated results with the observed data. The model parameters are then adjusted in subsequent simulations to improve the shape of simulated flow time-series until the model output meets the performance criteria. In general, the hydrological calibration for WaSh is conducted in three main steps:

1. Supplemental Irrigation: The total and supplemental irrigation demand and supply were determined through a review of previous modeling efforts and the Water Supply Plan.
2. Land Use Type Parameterization: Long-term simulations were conducted on representative land use types to obtain a target water budget for the particular land use.
3. Calibration and Validation of Basin Flow: Adjust hydrological parameters to obtain the long-term basin water budget and fine tune model parameters to get the best match between observed and simulated flow. At this stage, the shape of the hydrograph is adjusted with respect to peak and base flow.

Supplemental Irrigation Target

In the SLE watershed, the canal system primarily serves as a source of agricultural irrigation water and a mean to control water table levels to maximize crop production and reduce flood damages. Freshwater during the dry season is typically in short supply and the canal system is controlled to retain and reuse freshwater for irrigation to the maximum extent. It is common to supplement irrigation by groundwater in Floridian aquifer. However, site-specific data on irrigation application amounts, acreage, and timing were scarce. The sources for irrigation demand were determined by analyzing the water elevations in the primary canals. Estimation of the amounts of irrigation used by the citrus growers was conducted based on the observed daily water level, daily flow at water control structures of S-97 and S-49, and channel cross-section of C-23 and C-24 (Lin, 2001, Aqua-Terra, 1996). The daily withdraw was estimated by the daily stage difference and the stage-area-volume relationship derived from the channel cross-section. This amount was than increased by 30-40 % (derived from the Upper East Coast Regional Water Supply Plan developed in 1998) to cover the additional water withdrawn from deep groundwater source.

The SLE WaSh model assumes that approximately 70 percent of the irrigation demand supplied from the local canals which are subsequently replenished from the primary canal system. The remaining 30 percent of demand is obtained form the Floridian aquifer, which is considered an external source in this modeling application. These values are used in this model calibration as target values for demand and supply. The irrigation demand was first calibrated to target values for the irrigated agricultural lands. The model results show that annual average irrigation demand varied form cell to cell. The percentage of canal water and external (deep aquifer) water also varied between cells. This was due to shortages of canal water during extended drought periods. The shortage was automatically adjusted for in the model by increasing the external water supply. This effectively changes the ratio for canal to external water. With adjustment of the ET coefficients and supply parameters, an annual average of approximately 15 inches demand with a 70/30 split for canal and external supply was obtained as the target for citrus groves in the watershed.

Land Use Type Parameterization

A localized version of WaSh, called MicroWaSh was used for land use type parameterization. The MicroWaSh is a single cell version of WaSh that includes all of the functionality of WaSh except surface routing. Cell-based canals can be represented in MicroWaSh and the canals only act to provide local drainage. However, the canal water and groundwater interaction is retained in MicroWaSh, so the canal level does provide control over groundwater elevations MicroWash also contains the irrigation demand algorithms, but the supply algorithms which depend in part on water availability through surface routing are not included. Thus MicroWaSh can be used to calibrate demand, but the supplies.

The MicroWaSh was run for 41 years from 1965 to 2005 with the C-24 rainfall and ET as the input data. Model parameters representing HSPF processes, irrigation demands, canal depth and widths, and aquifer properties were adjusted to achieve a target water budget reported by the earlier HSPF model of Lin (1999). **Table C2-4** lists the resulting water budget of MircoWaSh simulations.

Table C2-4. Annual Average Water Budget of Representative Land Use Types from MicroWaSh Simulations.

LAND USE	RAINFALL (INCHES)	IRRIGATION (INCHES)	ET (INCHES)	RUNOFF (INCHES)
Groves	50.9	15.3	34.0	32.2
Pasture	50.9	0	34.1	16.8
Wetland	50.9	0	40.9	10.0
Forest	50.9	0	35.4	15.5
Urban (20% impervious area)	50.9	0	29.1	21.8
Urban (40% impervious area)	50.9	0	22.6	28.3

Calibration and Validation of Basin Flows

The subsequent calibration of the WaSh model in the basin scale considers cell to cell interactions such as groundwater flow between cells and changes of canal water levels due to flow routing and irrigation supplies. Certain cell parameters held constant during the MicroWaSh calibrations may also vary from cell to cell in the WaSh model implementation. The hydrologic calibration was conducted by adjusting citrus groves parameters to obtain the target irrigation demand and supplies, and then fine tuning model parameters to get the best match between observed and simulated flow at the basin discharge structures where observed data are available. The model parameters to be calibrated includes the groundwater cell conductance parameters that control the rate at which groundwater flows to the canals, the irrigation parameters, and the canal pumping parameters that control the rate at which tertiary canals flow to primary reaches. To a lesser degree, the length-scale parameter associated with surface drainage (LSUR) has an effect on the shape of the hydrographs. Reducing the LSUR increases runoff and decreases infiltration. The model validation process is similar to the calibration process, except that a different time period is used with all the model parameters kept unchanged.

Flow data collected at five flow structures including S-49 of C-24, S-97 and S-48 of C-23, S-80 and S-308 of C-44 (**Figure C2-3)** were used for model calibration and validation. All the collected flow data were evaluated for their validity before being used for model calibration and validation. The flow data collected at the Gordy Road Structure, G-81, G-79, G-78, and S-153 were not used due to the scarcity and reliability issue of the data. Flow data from 1994 to 2000 was used for model calibration and from 1965 to 1993 for model validation.

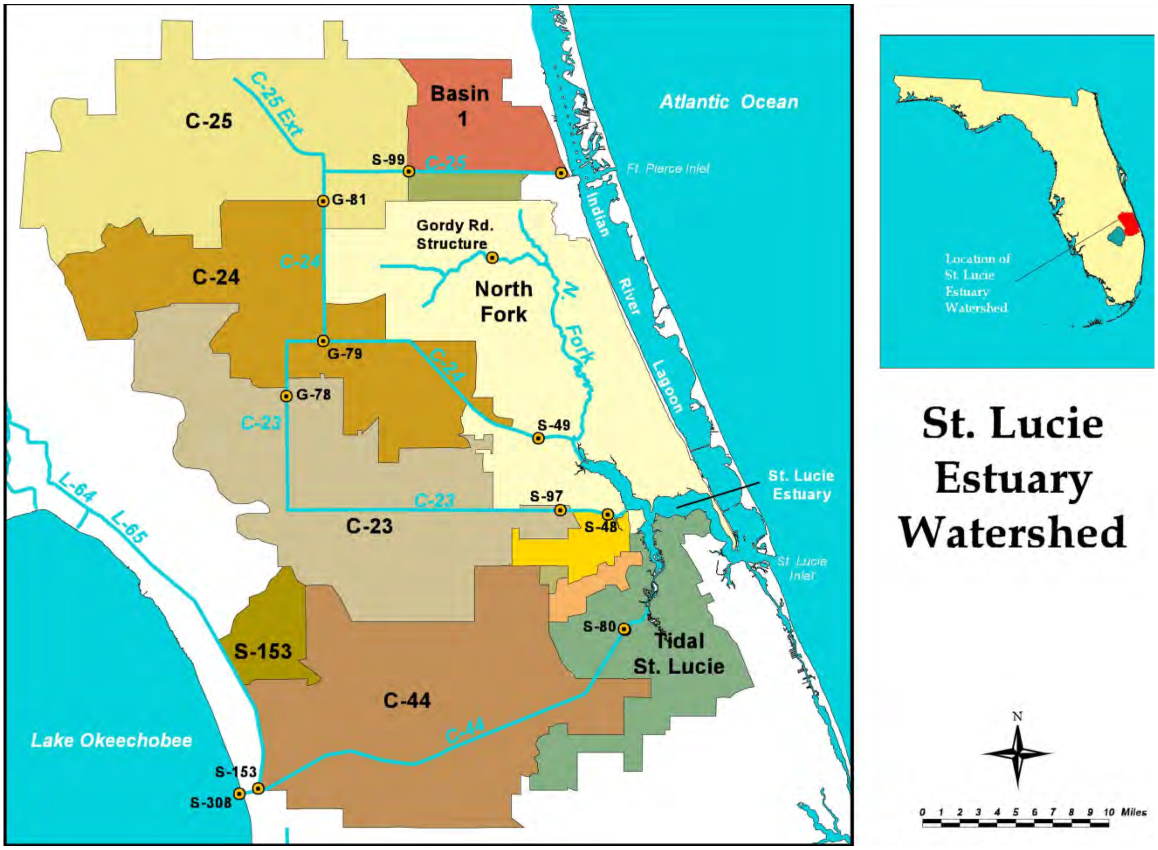


Figure C2-3. Flow Monitoring Stations in the Watershed for WaSh Model Calibration.

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

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

$$DV = \frac{\sum_{i=1}^{n}(Vm - Vs)}{\sum_{i=1}^{n} Vm} \times 100\% \qquad \text{[C2-11]}$$

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

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

$$NS = 1 - \frac{\sum_{i=1}^{n}(Qm - Qs)^2}{\sum_{i=1}^{n}(Qm - Q)^2} \qquad \text{[C2-12]}$$

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

The model calibration and validation performance results for C-24 and C-23 are summarized in **Table C2-5**. Calibration results for C-44 basin are not reported here since the C-44 Model was not used for model application in this project. In general, the model simulates daily flow reasonably well with R^2 and *NS* values above 0.6 for both C-23 and C-24 in the calibration period. The performance during the validation period is not as good as calibration most likely due to the longer time period and the change in land use and operation during the past several decades in the basins.

To aid in the evaluation of model calibration and validation performance, the double mass curve of the cumulative flow against cumulative rainfall were plotted in **Figure C2-4** at S-97 and S-49 for the calibration period (1994-2000) and validation period (1965-1993). The double mass curve is a visual check of the *DV* calculated in **Table C2-5.** It is shown that the modeled flow in general followed the pattern of the measured flow during both calibration and validation periods. The C-24 basin model tends to under-estimate flow though the actual ET is slightly lower than that of C-23 basin. Further improvement of the calibration can be obtained by considering inter-basin transfer between C-24 basin and C-25 basin via G-81. This inter-basin transfer occurs typically in high flow regimes though the measured data at G-81 is very limited.

Table C2-5. WaSh Model Calibration and Validation Performance Results.

MONITORING STATION	S-49 OF C-24	S-97 OF C-23
Calibration Results		
Calibration Period	1994–2000	1994–2000
DV (%)	12	–8
NS	0.60	0.64
R^2	0.61	0.68
Validation Results		
Validation Period	1965–1993	1965–1993
DV (%)	12	0
NS	0.46	0.17
R^2	0.47	0.25

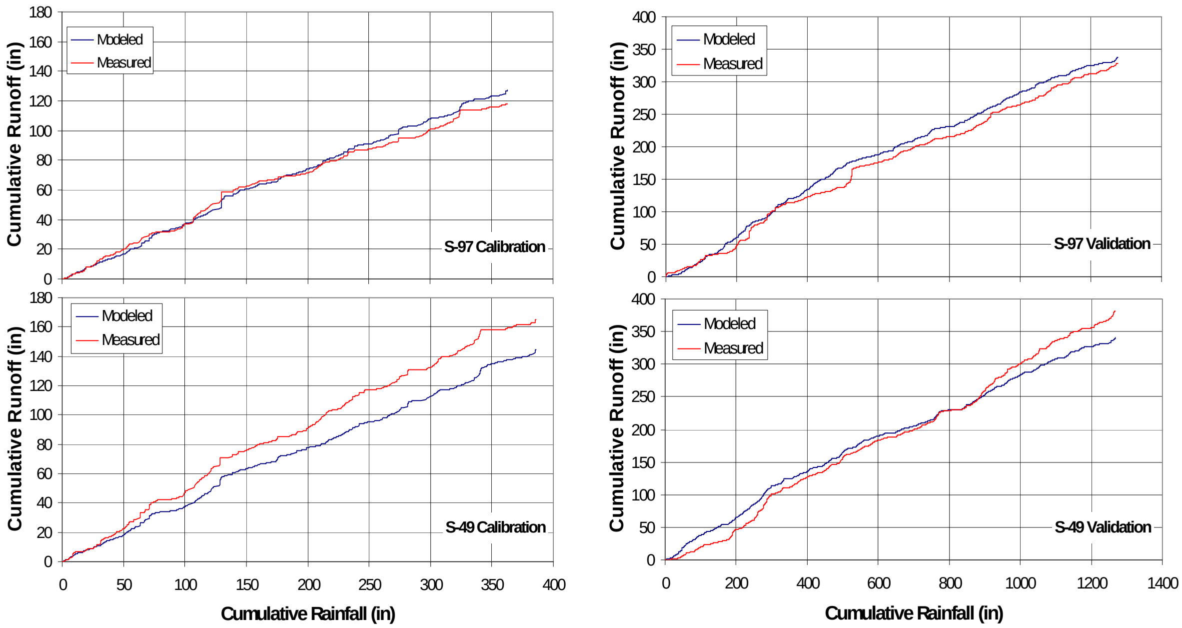


Figure C2-4. Double mass curve during the calibration period (1994–2000) and validation period (1965-1993) at S-97 and S-49 Stations.

Figure C2-5 shows the time series plot of the measure flow and simulated flow at Stations S-97 and S-49 for the period from 1997 to 2000. This period contained a hurricane in 1999 and the 2000 drought. The figure shows that the simulated flows were in general agreement with the measured flows at both locations. It needs to be noted that, for an extremely high flow event, the model tended to under estimate the peak flow for both C-23 and C-24.

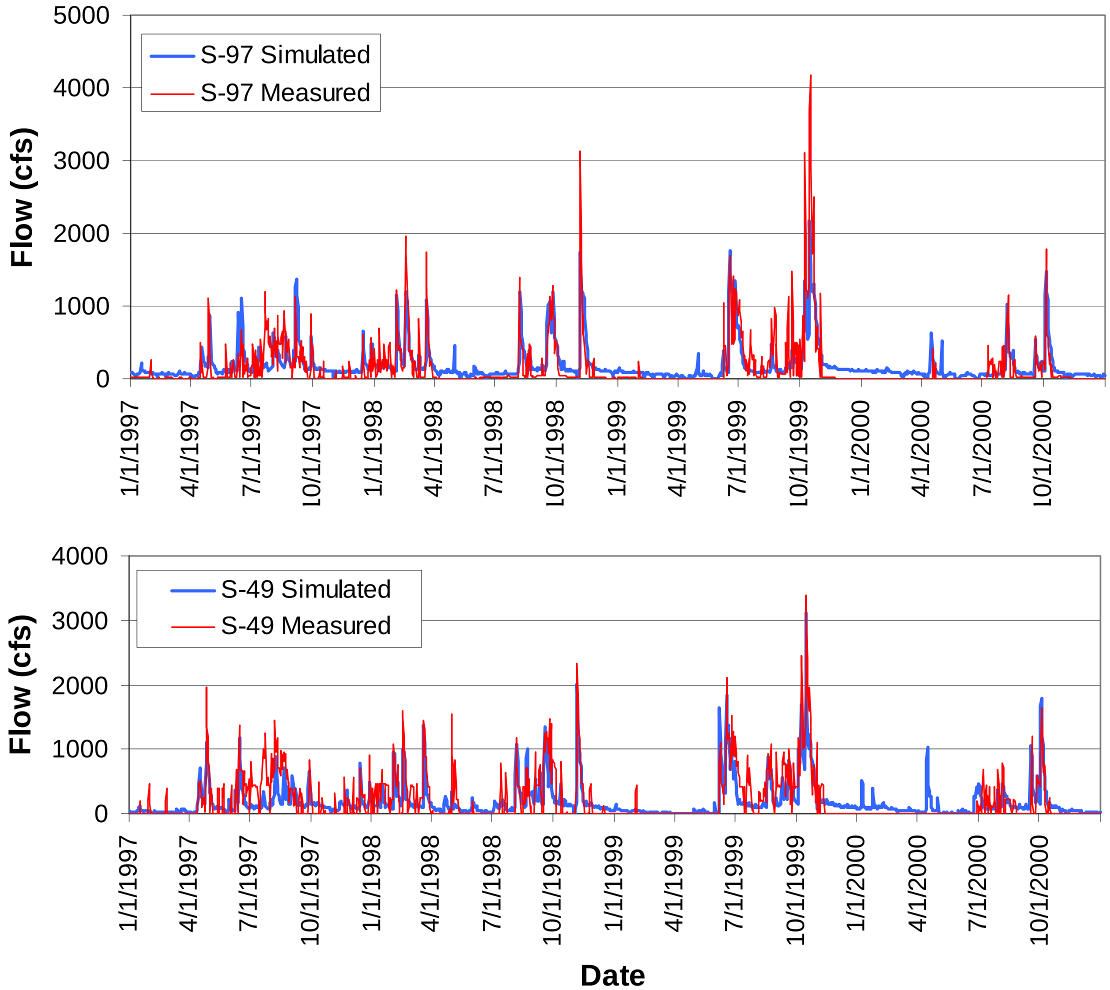


Figure C2-6. Comparisons between simulated and measured daily flow time series for the period from 1997 through 2000 at S-97 and S-49 Stations.

WaSh MODEL APPLICATIONS

A final long-term simulation for the period from 1965 to 2005 was conducted after land use adjustment to reflect the 2050 land use in each of the basins. **Table C2-6** shows the land use for each of the basins. Note that noticeable land use change compared with the 2000 land use is an increase in both the natural land to be restored in basins of C-23, C-24, C-44, and South Fork, and the urban land in the North Fork and South Fork basins. These changes are proposed in the Indian River Lagoon- South Feasibility Study as shown in **Figure C2-6**.

The simulated freshwater inflows into the estuary under the land use condition was further adjusted with the footprint of the reservoirs and stormwater treatment areas (STAs) proposed in the Indian River Lagoon- South Feasibility Study. The resulting hydrology was summarized in **Table C2-7**. The time series results are used as the input data of the OPTI6 model. Note that the C-44 Basin Model stormwater runoff and irrigation demand output were not used for the OPTI6 simulations in the Northern Everglades Program application. Instead, a C-44 basin AFSIRS/WATBAL Model (Smajstrla, 1990; Brion, 2008) developed by the Inter-Agency Modeling Center staff was used to irrigation demand. The AFSIRS/WATBAL model was used because the new stage of the Lake Okeechobee under the Northern Everglades Program needs to be used to route C-44 flow into the Lake when the lake stage is lower than 14.5 feet NGVD.

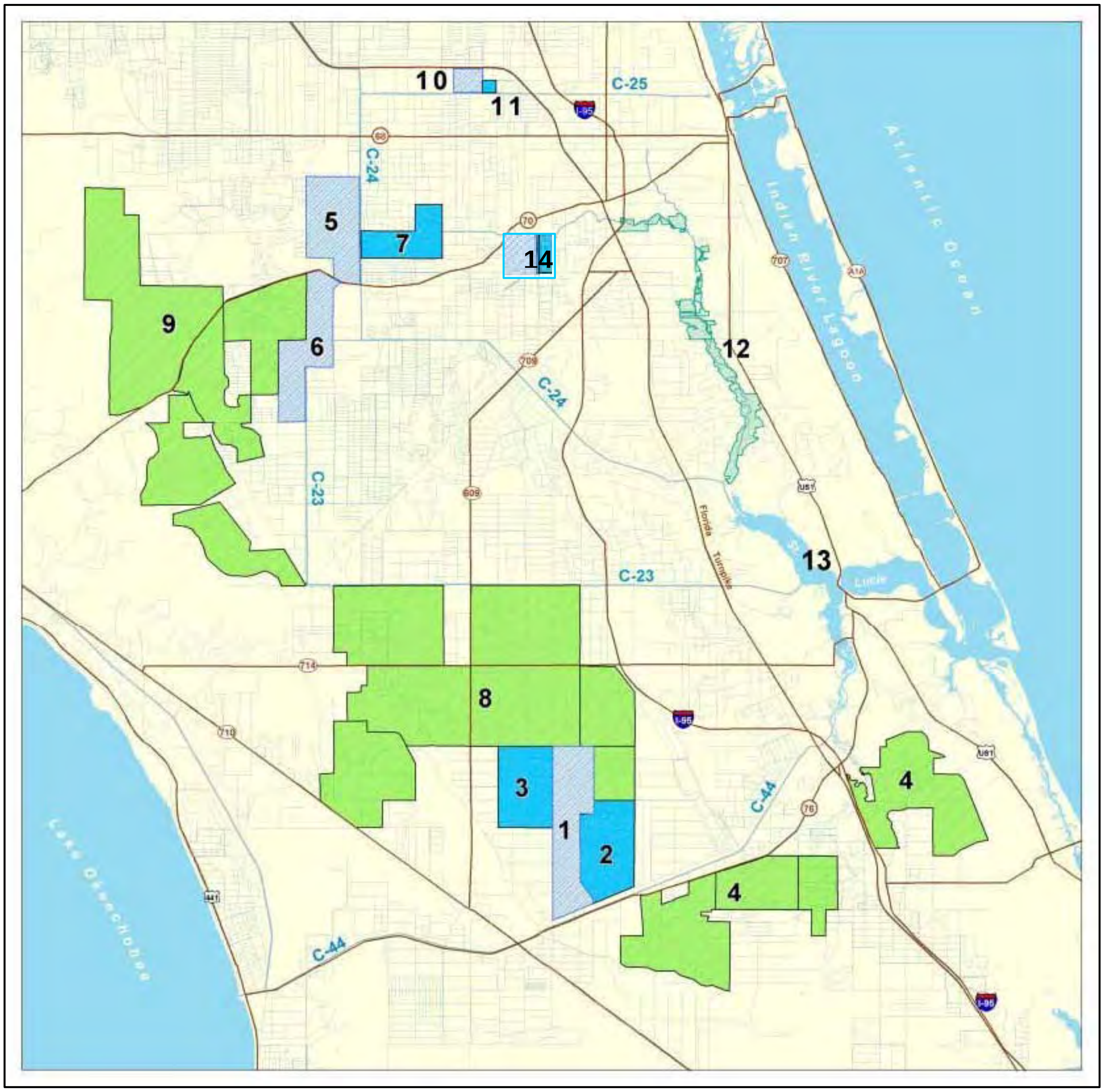
Table C2-6. The acreage of the 2050 land use change including the restored wetland in the St Lucie Estuary Watershed.

Basin	Forest	Citrus Grove	Pasture	Urban	Wetland [a]	Total
South Fork	5,089	5,977	5,752	14,897	17,129	48,843
Basins 4,5,6	2,913	689	844	8,977	1,321	14,744
North Fork - Tidal	2,640	746	359	61,500	11,060	76,305
North Fork – Ten Mile Creek	3,242	16,745	956	7,544	821	29,308
C-23	5,655	36,159	11,231	3,741	55,619	112,405
C-24	6,163	22,128	24,724	8,225	28,296	89,535
S-153	2,300	1,690	4,288	672	4,162	13,112
C-44	8,679	50,058	9,783	8,581	39,485	116,586
Total	36,681	134,192	57,937	114,137	157,893	500,838
Total in Percentage	7%	27%	12%	23%	32%	100%

[a] including nature land to be restored.

Table C2-7. The simulated annual average freshwater inflows into the St. Lucie Estuary.

Basin	Runoff to SLE (acre-feet/year)	Runoff to Lake (acre-feet/year)	Total flow (acre-feet/year)	Supplemental irrigation (acre-feet/year)
South Fork including basins 4,5,6	97,139		97,139	
North Fork	197,712		197,712	9,776
C-23	132,417		132,417	11,157
C-24	117,696		117,696	11,524
C-44 including S-153	87,987	75,099	163,086	29,153
Total	632,950	75,099	708,049	61,610



C-44 Basin Components

1 C-44 - Reservoir
2 C-44 - Stormwater Treatment Area(East)
3 C-44 - Stormwater Treatment Area(West)
4 Palmar Complex - Natural Storage and Water Quality Area

C-23/24 Basin Components

5 C-23/C-24 - North Reservoir
6 C-23/C-24 - South Reservoir
7 C-23/C-24 - Stormwater Treatment Area
8 Allapattah - Complex Natural Storage and Water Quality Area
9 Cypress Creek/Trail Ridge Complex - Natural Storage and Water Quality Area

C-25, Northfork and Southfork Basin Components

10 C-25 - Reservoir
11 C-25 - Stormwater Treatment Area
12 Northfork Natural Floodplain Restoration
13 Muck Remediation and Artificial Habitat
14 Ten Mile Creek Reservoir and STA

Natural Floodplain Restoration
Natural Storage and Water Quality Area
Reservoir
Stormwater Treatment Area

Figure C2-6. Project Features of the Indian River Lagoon South Feasibility Study.

C3. OPTIMIZING DELIVERY OF FRESHWATER INFLOWS AND RESERVIOR OPERATION USING OPTI6

Previous biological research and salinity modeling conducted by SFWMD (e.g., Haunert and Startzman, 1985; Hu, 1999) lead to the development of the "salinity envelope" concept. This understanding formed the basis to define a favorable range of watershed monthly inflows, which is from 350 to 2000 cfs, for juvenile marine fish and shellfish, oysters, and submerged aquatic vegetation in the estuary. The acceptable violations of this desired range, particularly in the high flow range, are defined by the frequency distribution of monthly inflows of the pre-drained watershed. To recapture the target monthly flow distribution, the Indian River Lagoon- South Feasibility Study proposed large storage reservoirs as a means of ecosystem restoration to store or diverts harmful basin runoff which is released to SLE when salinity conditions in the estuary could accommodate it. The OPTI model was developed to simulate the delivery of the flows in the reservoirs to meet the target flow distributions (Labadie, 1995 and 1997).

OPTI6 MODEL FORMULATION

Model Structure

Since 1997, South Florida Water Management District has been collaborating with Colorado State University to develop a water resources optimization model, OPTI, through different versions for Caloosahatchee River Watershed and St. Lucie River Watershed. The OPTI6 model is Version 6 (latest version) of the OPTI model developed for the restoration of the St. Lucie Estuary ecosystem. The model consists of a genetic algorithm (GA) module, fuzzy logic module, and a drainage network simulation model, see **Figure A3-1**. In the figure, $q_i^w(s_{i,t}, I_{i,t})$ and $q_i^s(s_{i,t}, I_{i,t})$ are operation rule of basin i on day t for winter and summer respectively. Details of the theory and the application of OPTI6 model can be found in Wan et al (2006).

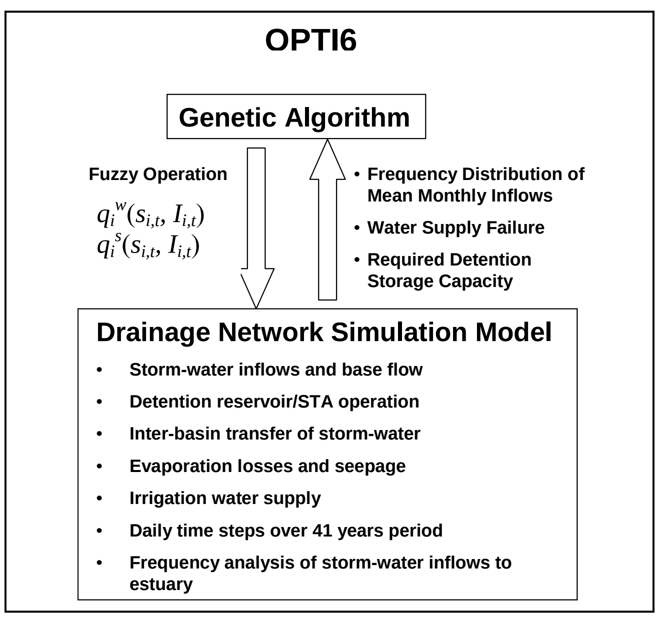


Figure C3-1. OPTI6: Interaction of genetic algorithm for optimizing fuzzy operating rules with drainage network simulation model (Wan et al., 2006).

Figure C3-1 shows the connection between the GA and the drainage network simulation model, where the GA selects populations of fuzzy consequence of the rule-based system, which are then evaluated through the daily drainage network simulation model. The daily drainage network simulation model evaluates mean monthly frequency distributions of freshwater inflows, water supply reliability, and required storage capacity, which are returned to the GA for improvement in the fitness. Detail description of genetic algorithm, fuzzy logic theory, and drainage network simulation model used in OPTI6 are presented in the following subsections.

Genetic Algorithm (GA)

A genetic algorithm (GA) is a search technique used in computing to find exact or approximate solutions to optimization and search problems. Genetic algorithms are categorized as global search heuristics. Genetic algorithms are a particular class of evolutionary algorithms (also known as evolutionary computation) that use techniques inspired by evolutionary biology such as inheritance, mutation, selection, and crossover (also called recombination). Genetic algorithms (GA's) have been successfully used in water resources engineering optimization (Monoliadis and Karantounias, 2003; Wardlaw and Bhaktikul, 2001 and 2004; Wan et al., 2006; Wu et al., 2001; and Yang and Soh, 1997). In the OPTI6, genetic algorithms (GA's) are applied to optimize water control structure operation since it requires no explicit analytical representation of the objective function and constraint sets in the optimization. No information on gradients is required and discontinuities in the objective function appear to have little effect since GA's are resistant to becoming trapped in local optima.

Rooted in the mechanisms of natural selection in biology, genetic algorithms were first proposed by Holland (1975), whose goals were to explain the adaptive processes of natural systems and design computing systems embodying their important mechanisms. With Goldberg's (1989) book, which completely covers GA concepts, mathematical foundations, implementation, and applications, researchers in a wide variety of fields have attempted to apply GA's. GA's have proven to be particularly attractive for solving complex combinatorial problems quickly and reliably, as well as providing easy interfacing to existing simulation models, and have therefore become the evolutionary computation method of choice.

Genetic algorithms differ from traditional optimization methods in that: (i) they operate on a binary string coding of the variables (genotype), rather than the actual real-numbered values (phenotype) of the variables; (ii) rather than searching over sequential points in the solution space, a GA generates an entire population of solutions at each step (generation); and (iii) random processes play an important role in a GA. Real variables are coded into binary strings such as [1 0 0 1 1 0 1 0], whose phenotype value is 154. The length of the string depends on the size and precision of the real number being coded. The biological analogy is that this represents a chromosome, with each bit representing a gene in the chromosome with a particular locus or position in the string. For binary-coded strings, the allele of each gene is the value 0 or 1.

The genetic algorithm driver Program *gafortran* from Dr. David Carroll (CU Aerospace, Inc., Champaign, Illinois; http://cuaerospace.com/carroll) was obtained as freeware for use in OPTI6. Since Version 1.7 of gafortran is written in FORTRAN 90, the program was converted to ANSI C in order to maintain compatibility with other C/C++ software. The converted C code gaopt uses standard C libraries and is readily compiled with the Gnu gcc compiler.

The GA implemented in OPTI6 has evolution via survival of the fittest. The selection scheme used in the GA is tournament selection with a shuffling technique for choosing random pairs for mating. The routine applied in the GA includes binary coding for the individuals, jump mutation, creep mutation, and the option for single-point or uniform crossover. Uniform crossover is used in OPTI6 implemented in IRL-S Reservation project. Niching (sharing) and an option for the number of children per pair of parents have been added to the model. Niching is implemented through Goldberg's multidimensional phenotypic sharing scheme with a triangular sharing function (Goldberg, 1989). To find the multidimensional distance from the best individual, all parameter differences are normalized. In the OPTI6, GA uses the following parameters, which are recommended in gafortran from Dr. David Carroll: population size of a generation is 100; a chromosome is represented by a binary string length of 9; jump mutation probability is 0.01 and creep mutation probability is 0.02; uniform crossover probability is 0.5.

Fuzzy Logic Theory

In OPTI 6, fuzzy operating rules was used to generate the optimal reservoir operating rules to represent feedback policies whereby operators measure current day inflows and reservoir storage, and then obtain reservoir operation guidelines from the rules based on those measurements as well as the time of year. The original operating rules in previous versions of OPTI aggregated the storage and inflow measurements together using various weighting factors, meaning it was possible that one day with high inflow and low storage measurements could result in the same operational guidelines as a day with low inflow and high storage conditions. To overcome this problem, it was decided to develop fuzzy operating rules that allow inflow and storage conditions to be distinguishable to the operators and produce unique rules for all combinations of inflow and storage conditions on any day. Fuzzy rules also have the advantage of not requiring an a priori mathematical structure for the rules, such as linear decision rules.

The general structure of a fuzzy rule n is (Bárdossy and Duckstein, 1995):

$$If\ a_1\ is\ A_{n1} \Theta\ a_2\ is\ A_{n2}\ \Theta \cdots \Theta\, a_k\ is\ A_{nk} \quad Then \quad B_n \qquad [C3\text{-}1]$$

where the boolean logical operator Θ refers to "AND", "OR", or "XOR". The IF part of the rule represents the premises and the THEN part is termed the consequence. Arguments in the rule premise are assumed to belong to fuzzy sets, and the consequence also belongs to a fuzzy set. In contrast with crisp sets, a fuzzy set assigns a membership value or degree-of-truth to elements of the set. The membership values vary between 0 (indicating no truth to the assertion that the element is a member of the set) to 1 (indicating complete confidence in the assertion). For each set of facts provided to the fuzzy rules (i.e., current measurements of inflows and storage in this case), a degree of fulfillment (DOF) for basin *i* is calculated for the premises of each rule *n*. Although there are number of ways of calculating DOF, the most popular is product inference. For this case, product inference calculates DOF (for "AND" Boolean logic in the premises) as:

$$v_{i,n}(I_{i,t}, s_{i,t}) = (A_{i,n1}\ AND\ A_{i,n2}) = \mu_{A_{i,n1}}(I_{i,t}) \cdot \mu_{A_{i,n2}}(s_{i,t}) \qquad [C3\text{-}2]$$

where $\mu_{A_{nk}}(a_k)$ is the membership value (between 0 and 1) of argument a_k($I_{i,t}$ when k=1: inflow; $s_{i,t}$ when k=2: storage) in fuzzy set of rule *n* for basin *i*. Since fuzzy rule-based systems are distinguished by the fact that several rules can be simultaneously activated for a given set of measurements, but at varying degrees of fulfillment, a method is needed for combining the fuzzy consequences of each of the rules. The normal weighted sum combination method has been used to calculate combination of the fuzzy consequences of each rule. With the most popular deduzification method, mean defuzzification, the combination of fuzzy consequences is defuzzified and converted to a crisp value which is operating rule conditioned on the current inflow and storage measurements supplied as facts to the fuzzy rule-based system.

For this application, the fuzzy membership functions for the premises are assumed to be structured as symmetric, triangular fuzzy numbers. In the model, there are two types of premise arguments: available storage at the beginning of the current day and expected basin inflow for the current day. These quantities are converted to units of inches over the basin. The range for each type of argument is determined using the maximum storage capacity for each basin and then calculating the largest daily inflow that occurred during the simulation period. The desired numbers of arguments for each type of premise (i.e. storage or inflow) are pre-determined for each basin before model application. The model checks the amount of freshwater inflow and the reservoir storage to calculate the combination of fuzzy of consequences of a series of rules. After which, the model defuzzy the fuzzy consequences to a crisp value as operation rule. Then the pump flow or reservoir release flow was computed used the defuzzified rule. In order to relate the operating rules to seasonal influences, distinct rules are developed for both dry season and wet season.

Drainage Network Simulation Model

Solution of Eq. [13] requires daily simulation of the drainage network for calculation of the mean monthly probabilities F_c for all frequency classes c of stormwater releases to the SLE. In OPTI6, the drainage network simulation assumes the reservoirs are off-stream reservoirs requiring pumping facilities for both diversion into and release from the reservoirs, as depicted in **Figure C3-2**. It is also assumed that a multi-cell STA is connected to each detention reservoir for reducing loads of nutrients, pesticides, and other pollutants from stormwater runoff. The mass balance equation for the reservoirs with connected STA is:

$$s_{i,t+1} = s_{i,t} + d_{i,t} - q_{i,t} + (rain_{i,t} - evap_{i,t}) \cdot A(s_{i,t}) - seep_i \cdot s_{i,t}$$
$$(\,for\ i = 1,...,nb;\, t = 1,...,nd\,) \qquad [C3\text{-}3]$$

where $s_{i,t}$ is storage in basin i at the beginning of day t, combining both reservoir and STA storage; $A(s_{i,t})$ is surface area of basin i as a function of storage $s_{i,t}$; $d_{i,t}$ is pumped discharge into reservoir i from the adjacent canal; q_{it} is pumped release from the STA to the canal; $rain_{i,t}$ and $evap_{i,t}$ are rainfall and evaporation rates, respectively, for basin i on day t; $seep_i$ is the seepage fraction per unit storage for basin i, and nd is the total number of days in the simulation. The simulation assumes that a portion of the reservoir/STA seepage can return as lagged flow to the canal and is added to the freshwater release to the SLE.

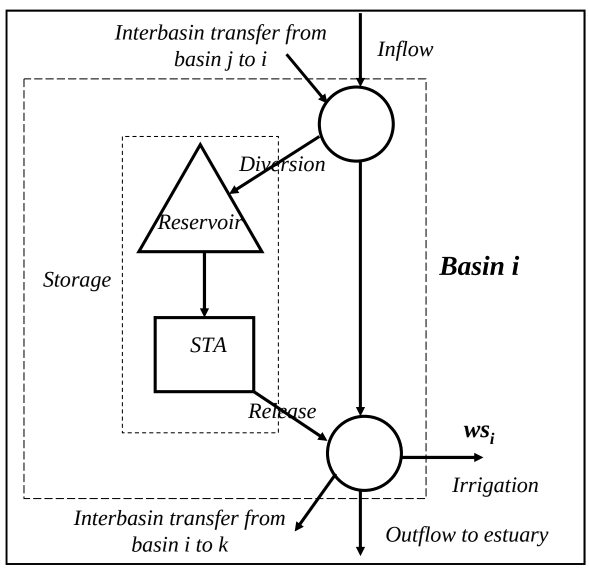


Figure C3-2. Schematic of typical off-stream reservoir with connected storm-water treatment area (Wan et al., 2006).

The following bounds on the variables are imposed during solution of Eq [13]:

$$\left.\begin{aligned} 0 \le s_{i,t+1} \le s_{i,\max} \\ 0 \le d_{i,t+1} \le d_{i,\max} \\ 0 \le q_{i,t+1} \le q_{i,\max} \end{aligned}\right\} for\ i = 1,\cdots,nb;\ t = 1,\cdots,nd \qquad \begin{matrix}[C3\text{-}4]\\ [C3\text{-}5]\\ [C3\text{-}6]\end{matrix}$$

The primary decision variables in the optimization are the scheduling of diversions $d_{i,t}$ pumped into the reservoir/STA and discharges $q_{i,t}$ pumped out of the basin. However, since it makes little sense to allow for both $d_{i,t}$ and $q_{i,t}$ on any day t, the decision variables can be simplified as the net inflow to the reservoir: $[d_{i,t} - q_{i,t}]$.

At the beginning of each day, attempts are first made to satisfy the water supply requirements for irrigation $ws_{i,t}$ by removing water in storage in the reservoir (relaxing the restriction of $q_{i,max}$). If there is insufficient available storage to satisfy the irrigation demand, then the remainder is supplied from basin inflow and transbasin diversions. The irrigation demand is delivered only if it can be fully satisfied for that day, with partial fulfillment of water supply not allowed. If there is insufficient available water in storage (at the beginning of the day) and inflow, then a water supply failure is assumed to occur for that day. The remaining flow is available for diversion into the reservoir/STA. That is:

$$\begin{aligned}
&IF: \quad I_{i,t} + \sum_j qtrans_{j,i,t} + s_{i,t} \ge ws_{i,t} \\
&THEN: \\
&\qquad IF: \quad I_{i,t} + \sum_j qtrans_{j,i,t} - ws_{i,t} > 0 \\
&\qquad THEN: qavail_{i,t} = I_{i,t} + \sum_j qtrans_{j,i,t} - ws_{i,t} \\
&\qquad ELSE: qavail_{i,t} = I_{i,t} + \sum_j qtrans_{j,i,t} + s_{i,t} - ws_{i,t} \\
&\qquad\qquad s_{i,t} \leftarrow s_{i,t} - I_{i,t} - \sum_j qtrans_{j,i,t} + ws_{i,t} \\
&ELSE: ws_{i,t} = 0 \\
&\qquad wsfail_i \leftarrow wsfail_i + 1 \\
&\qquad qavail_{i,t} = I_{i,t} + \sum_j qtrans_{j,i,t}
\end{aligned}$$

where $qtrans_{jit}$ $qtrans_{j,i,t}$ is the interbasin transfer of flow from basin j to i on day t; $qavail_{i,t}$ is the remaining canal flow available for diversion to the reservoir/STA on day t; $ws_{i,t}$ is the irrigation demand on day t; and $wsfail_i$ counts the number of days of water supply failure during each year of the simulation for basin i.

Transbasin diversions $qtrans_{j,i,t}$ are given a high priority in the simulation and are assumed to occur up to the pumping capacity if flow is available (i.e., after irrigation demands are satisfied). The importance of transbasin diversions is to enhance the health of the Estuary when excess freshwater releases can be diverted to the North Fork area via Ten Mile Creek, or south to C-44. This reduces freshwater releases from the C-23 canal into the middle of the SLE and enhances the salinity balance. Any desired transbasin transfer configuration can be specified in the simulation model, and transfers can be made to more than one basin. Maximum transbasin diversion amounts can be specified, along with additional restrictions if flooding would occur in the receiving basin. Special rules regarding basins such as in C-44 are required when levels in Lake Okeechobee dictate when flows can go west to the Lake or east to the SLE. An option included in the simulation logic allows for special circumstances such as the reservoirs in C-23 and C-24 connected by an uncontrolled inverted siphon. A reservoir rebalance routine can be invoked whereby storage in the connected reservoirs is assumed to be balanced at the end of each day (in proportion to their relative storage capacities).

Model Objective Function

A weighting method of multi-objective optimization is applied in defining the objective function of the OPTI6. The model was originally designed to optimize watershed reservoir operation to meet the total inflow to SLE target distribution, irrigation demand, and minimum required reservoir storage capacity, without considering the North Fork inflow requirement for maintaining low salinity zone. For model application to St. Lucie River Watershed water reservation for North Fork low salinity zone project, the model objective function is revised to include the North Fork inflow demand constraint. Through this revision, the model is able to determines optimal size and operating rules for detention reservoirs in the SLE watershed that: (1) achieve a specified water demand to the North Fork from Ten Mile Creek for maintaining low salinity zone (from Midway Bridge to Kelstadt Bridge along North Fork) in dry season, (2) achieve the target frequency distribution of flows to the Estuary, (3) supply water from the watershed and reservoirs to satisfy the Floridan irrigation demands for at least a specified reliability, and (4) minimize the required capacities of the detention reservoirs. The objective function incorporating these criteria is defined as:

$$\text{minimize} \quad \{\sum_{cTMC=1}^{ncTMC} w_{cTMC}(100F_{cTMC} - 100T_{cTMC}) + \sum_{c=1}^{nc} w_c(100F_c - 100T_c) + \sum_{i=1}^{nb}[w_I(100P_i - 100\alpha)^2 \ \mathit{if}\ P_i > \alpha;\ 0 \text{ otherwise}] + \sum_{i=1}^{nb} w_S \cdot s_{i,\max}^2\} \qquad \text{[C3-7]}$$

where F_{cTMC} is the frequency distribution of mean monthly freshwater release to the North Fork from Ten Mile Creek within discrete flow ranges $cTMC = 1, \ldots, ncTMC$; T_{cTMC} is the target probability of mean monthly stormwater runoff to the North Fork from Ten Mile Creek at Gordy Road within the discrete flow range represented by class *cTMC*; F_c is the frequency distribution of mean monthly freshwater release to the SLE within discrete flow ranges *c*; T_c is the target probability of mean monthly stormwater runoff to the SLE within the discrete flow range represented by class *c*; P_i is the probability of failing to meet the water supply requirements for irrigation associated with storage option *i* in any year; α is the acceptable risk level for water supply, which is typically the 1-in-10 year drought in the SLE watershed; w_c $(c=1, \ldots, nc)$ are weighting factors providing a subjective rating of the relative importance of meeting each criterion for *nc* discrete flow frequency classes; w_I is a weighting factor associated with violating the risk target for irrigation water supply; w_S is a weighting factor associated with minimizing storage capacity requirements of each detention reservoir/STA(stormwater treatment area); *nb* is the number of stormwater reservoirs; and $s_{i,max}$ is the maximum storage capacity actually used in storage option *i* based on hydrologic simulation of the system.

OPTI6 APPLICATIONS

Hydrologic Input Data and Model Parameters

Application of OPTI6 requires daily watershed stormwater runoff data as well as irrigation demand on the Floridian Aquifer as the input data. The WaSh model provided this daily time series data from 1965 to 2005 under the 2050 land use and the proposed wetland restoration conditions for C-23 Basin, C-24 Basin, North Fork Basin, and South Fork Basin (including Basin 4, 5, &6). The daily time series data of C-44 basin was obtained from AFSIRS/WATBAL model. The C-44 Basin is linked to Lake Okeechobee by the C-44 Canal. The simulation of C-44 Basin hydrology needs to consider the impact of the lake operation. AFSIRS/WATBAL model developed for C-44 accommodates the lake operation impact. The NETP (Northern Everglades Technical Plan?) team decided to use AFSIRS/WATBAL model simulated stormwater runoff and irrigation demand as OPTI6 input in C-44 Basin. The daily rainfall and ET data used in WaSh were also used in the OPTI6. The monthly flow distribution targets used in the feasibility study (Haunert and Konya, 2001) were retained in this application. The monthly flow distribution target, particularly for the high flows were based on the modeling of the St. Lucie Estuary Watershed under the natural condition by Van Zee (2001). The Lake Okeechobee stage under the future of the Northern Everglades Technical Plan implementation was used as for this OPTI6 application. The required monthly Ten Mile Creek flow to North Fork at Gordy Road is larger than 130 cfs.

Table C3-1 details the area, depth, and storage capacity of the Reservoir/STAs, diversion pump capacities, and outflow (release) capacities proposed in the Indian River Lagoon south Feasibility Study. Note that the project feature of the C-44 reservoir and STAs are updated based the latest design information of the C-44 Accelor8 Project. The inter-basin transfer capacities are listed in **Table A3-2**. The OPTI6 was run from 1965 to 2005 with the stormwater runoff data and project features mentioned afore. The optimization results are presented and discussed in next subsection.

Table C3-1. The reservoirs and STAs implemented in the OPTI6 model.

Project Feature	Area (acres)	Depth (feet)	Storage (acre-feet)	Maximum inflow capacity (cfs)	Maximum out flow capacity (cfs)
Ten Mille Creek Reservoir and STA in North Fork	829	7.8	6,462	360	200
C-23 Reservoir	4,399	10.1	44,588	900	1,000
C-24 Reservoir and STAs	6,723	7.1	47,481	900	200
C-44 Reservoir and STAs	9,700	5.2	50,246	1,060	550

Table C3-2. The reservoirs/STAs interbasin transfer capacity in the OPTI6 model.

Project Feature	C-23 and C-24 reservoirs	C-24 STAs to Ten Mile Creek	C-23 Reservoir to C-44 Reservoirs	C-44 to Lake Okeechobee
Transfer Capacity (cfs)	1,000	200	250	20,000
Operation purpose	Equalize storage in reservoirs, limit to capacity of siphon	Maximize flow to TMC but keep flow at Gordy Rd < 200 cfs	Minimize C-23 releases	Regional water supply

Simulation Results Discussion

The OPTI6 was run from 1965 to 2005 with the parameters and data described in previous subsection. The annual water flow components of model output are calculated and showed in **Figure C3-3** that shows significant portion water is moved to North Fork from C-23 and C-24 Basins while also some water is moved to C-44 from C-23 and C-24 Basin. Flow into SLE and Ten Mile Creek flow into North Fork at Gordy Road distribution comparisons between 2050 Base with and without project condition are presented in **Table C3-3.** The table includes the target flow distribution as well. North Fork tidal basin and South Fork tidal basin (including Basin 4, 5, &6) stormwater and groundwater are not controllable and were not involved in optimization, meaning that they discharge into the estuary directly. From **Table C3-3**, the months with mean monthly flow of Tem Mile Creek into North Fork larger than 130 cfs increase from 166 (33.7%) to 450 (91.5%) through optimization of reservoir/STA operation. Only 42 months (8.5%) have the mean monthly flow less than 130 cfs. This is a significant improvement in the pattern of Ten Mile Creek flow to North Fork, which will well maintain low salinity zone from Midway Bridge to Kelstadt Bridge. **Figure C3-4** is the plot of the mean monthly flow of Ten Mile Creek to North Fork at Gordy Road of 2050 base with and without project conditions. The figure shows the mean monthly flows significantly are improved. Only extremely dry year, the mean monthly flow can not be maintained, such as 1980~1981 and 1989.

In **Table C3-3**, the improvement in the pattern of total flow into SLE is showed as well. The significant improvement can be observed in high flow which is critical to the estuary ecosystem. The months with the mean monthly flow to SLE between 2000 cfs and 3000 cfs reduce from 39 months (7.9%) to 23 months (4.7%, meets the target) while months with mean monthly flow greater than 3000 cfs reduce from 15 months (3.0%) to 5 months (1.0%, better than target, 7 months, 1.4%) . Improvement is also obtained for low flow. The months with monthly flow to SLE less than 350 cfs decrease from 154 months (31.3%) to 144 months (29.3%). The flow range between 350 cfs and 200 cfs is the favorable zone of SLE ecologic system. The months with mean monthly flow in this favorable zone increase from 284 (57.7%) to 320 (65%). **Figure C3-5** shows the mean monthly flow of total flow into SLE.

This simulation objective primarily focuses on maintaining mean monthly flow of Ten Mile Creek to North Fork larger than 130 cfs and reduction of the months of high flow to SLE to meet the target high flow pattern. The model has achieved these primary objectives and improve low flow pattern as well.

The OPTI6 also minimizes the irrigation failure frequency while optimizing the fresh water inflow to SLE. 1-in-10 year (10%) is used as irrigation failure frequency criteria for all sub-basins. The final frequency of irrigation failure output form the OPTI6 is listed in **Table C3-4**. It is apparent that the irrigation requirements were successfully met. The table also lists the amount of irrigation water from reservoirs in each sub-basin.

The flow time series of the OPTI6, including C-23 flow to SLE, C-24 flow to SLE, C-44 flow to SLE, Ten Mile Creek flow to North Fork at Gordy Road, North Fork tidal basin flow to SLE, and South Fork tidal basin (including Basin 4, 5, & 6) are provided to SLE Estuary hydrodynamic and salinity model for salinity evaluation use.

Table C3-3. Comparison of flow frequency Distribution before and after Optimization

Flow Class (cfs)	2050 Base without Project		Target		2050 Base with Project	
	Months	Flow Distribution (%)	Months	Flow Distribution (%)	Months	Flow Distribution (%)
Ten Mile Creek flow to North Fork at Gordy Road						
<130	296	60.2	49	10	42	8.5
≥130	196	39.8	443	90	450	91.5
Total Flow to SLE						
<350	154	31.3	< 235	< 47.8	144	29.3
350 ~ 2000	284	57.7	> 227	> 46.1	320	65.0
2000 ~ 3000	39	7.9	23	4.7	23	4.7
> 30000	15	3.0	7	1.4	5	1.0

Table C3-4. The Irrigation failure frequency and irrigation water from reservoir reservoirs and STAs simulated by the OPTI6 model.

Basins	Frequency of irrigation failure (%)	Irrigation water from reservoir (K*ac-ft/yr)
C-23	2.8	12.82
C-24	3.0	6.96
North Fork	1.5	6.38
South Fork	0	0.0
C-44	10.0	15.48

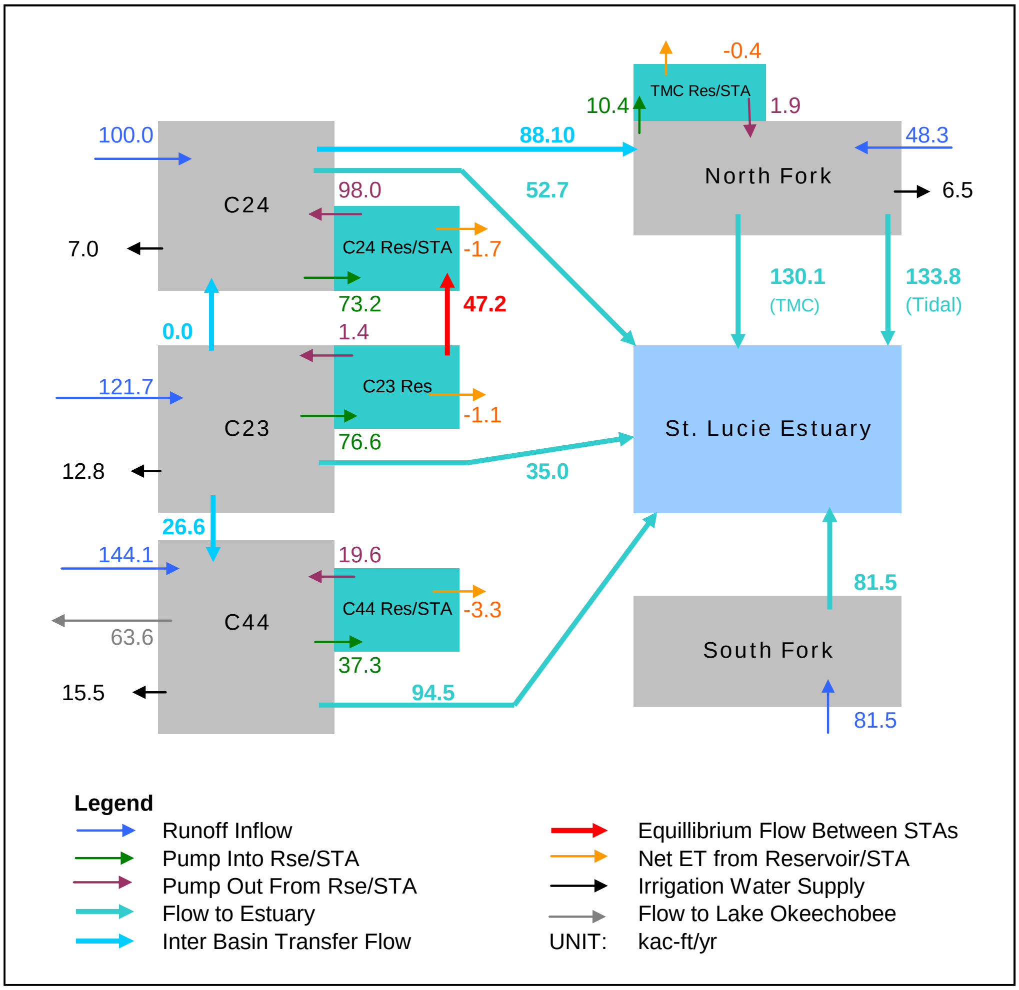


Figure C-3. Annual water budget of OPTI6 simulation results for the period from 1965 to 2005.

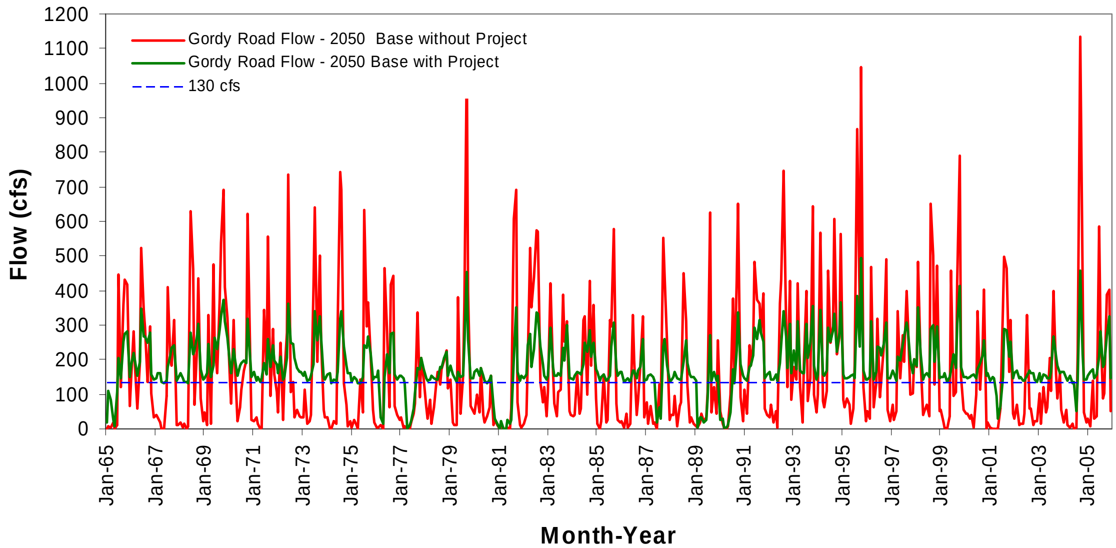


Figure C3-4. Ten Mile Creek Flow Comparison: 2050 Base with and without Project Condition.

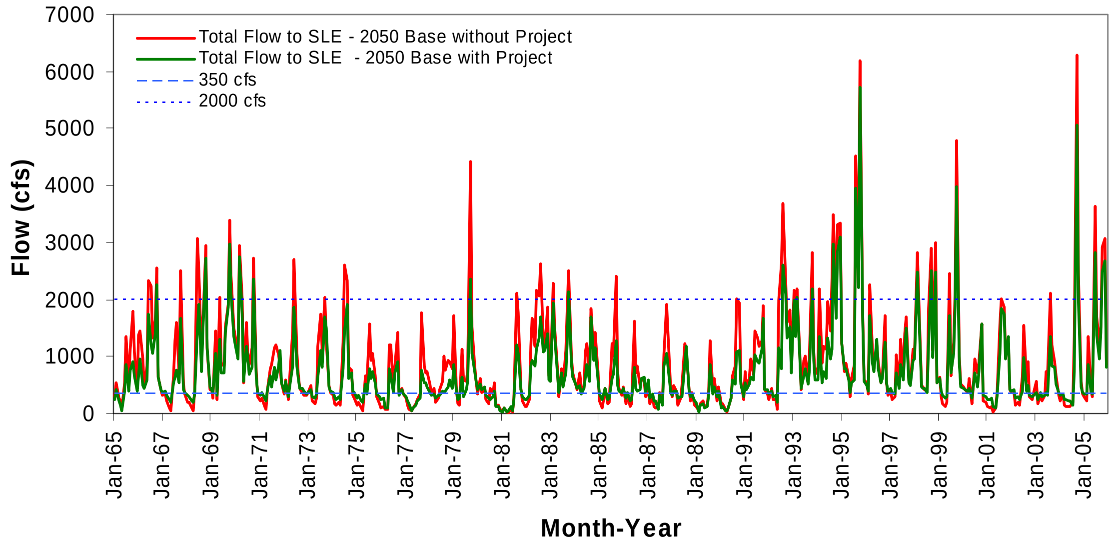


Figure C3-5. Total Flow to SLE Comparison: 2050 Base with and without Project Condition.

C4. SUMMARY AND CONCLUSIONS

In this modeling effort, the WaSh, a watershed hydrologic model, is used to simulate the stormwater runoff in C-23 basin, C-24 Basin, North Fork tidal and non-tidal basin, South Fork tidal basin (including Basin 4, 5 &6). C-44 Basin stormwater runoff is obtained from AFSIRS/WATBAL model output. The simulation was conducted under 2050 Base land use without project condition from 1965 to 2005. With project condition, the stormwater flows into SLE watershed can be changed by operating reservoirs/STAs to meet the flow pattern required for maintain SLE ecosystem heath. The primary objectives include (1) maintain Ten Mile Creek flow to North Fork at Gordy Road >130 cfs, (2) reduce months of low flow (<350 cfs) and high flow (>2000 cfs) to SLE, and (3) reduce irrigation failure frequency. An optimization model, OPTI6, is employed to achieve these objectives. The OPTI6 applies genetic algorithm, fuzzy logic theory, and a daily drainage network simulation model to optimize reservoir/STA operation. The model objective function is revised to include all objectives and the model is run for 1965 ~ 2005.

Monthly flows are calculated to compare with target flow pattern for model performance evaluation. The monthly flow comparison shows that the Ten Mile Creek flow to North Fork at Gordy Road is well maintained (91.5% months of 41 years has monthly flow larger than 130 cfs which is monthly flow required to maintain low salinity zone from Midway Bridge to Kelstadt Bridge) and the months of low flow (<350 cfs) and high flow (>2000 cfs) are significantly reduced to meet target. Additionally, the optimization result shows that the irrigation requirements are successfully met for all basins. Apparently, the combined use of watershed hydrologic model with watershed optimization model can achieve the project objectives. The operation optimized by the model can change the flow pattern to meet SLE ecosystem needs.

The optimized flow time series are provided to SLE hydrodynamic and salinity model for salinity variation evaluation for whole estuary.

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Appendix D.
Development of CH3D Hydrodynamic/Salinity Model for St. Lucie Estuary, Florida

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South Florida Water Management District

Introduction

The St. Lucie Estuary (SLE) is a riverine estuary located on the east coast of south Florida (Figure 1). The estuary discharges into the southern end of the Indian River Lagoon (IRL), which is connected with the Atlantic Ocean via the St. Lucie Inlet. The SLE has a total area of about 29 km^2. Except for the man-made navigation channel, the estuary is very shallow with a mean water depth of about 2.4 m. The estuary receives freshwater inflows from two natural tributaries, the North Fork (NF) and the South Fork (SF) and three drainage canals, namely C-23, C-24, and C-44. The complexity of the bathymetry with navigation channel, multiple inlets, and shallow disposal area results in a unique estuary-lagoon system, where both surface runoff and sub-estuary exchange affect the estuary circulation. Because of the restricted connections with the ocean, tidal ranges in the SLE are relative small. Thus wind and freshwater buoyancy inputs are influential on the estuary dynamics.

The SLE/IRL system has suffered from altered freshwater flow patterns and degraded water quality due to dramatic changes in land use, drainage, and stormwater quality over the last 100 years in the upstream watershed (Grave et al 2004, Wan et al. 2006). Floodwater released to the estuary from Lake Okeechobee, combined with excess stormwater runoff from drainage canals, altered salinity balance and stressed the estuary's unique ecosystem. Seagrasses and oysters, once abundant in the estuary, become virtually absent (Haunert and Startzman 1980, 1985). The SLE is now a phytoplankton-based system with high chlorophyll *a* concentrations (blooms exceeding 50 µg chl *a*/l have been observed, maximum = 73.3 µg chl *a*/L) with hypoxic and anoxic events in bottom waters (Chamberlain and Hayward 1996, Doering 1996). To address these issues, the Florida legislature designated the SLE as a Surface Water Improvement and Management (SWIM) priority water body. This effort is continued through the current SLE/IRL ecosystem restoration plan undertaken by the South Florida Water Management District (SFWMD or District) and the United States Army Corps of Engineers (USACOE) through the Comprehensive Everglades Restoration Plan. This restoration plan aims to re-establish an appropriate salinity regime and improve water-quality conditions in the estuary through construction of large regional reservoirs and stormwater treatment areas (Wan et al. 2006). A central tool for aiding in these efforts is an integrated modeling system capable of simulating estuary circulation, suspended sediment transport, and water quality processes. The hydrodynamic modeling of the SLE/IRL is one critical component of the integrated modeling system.

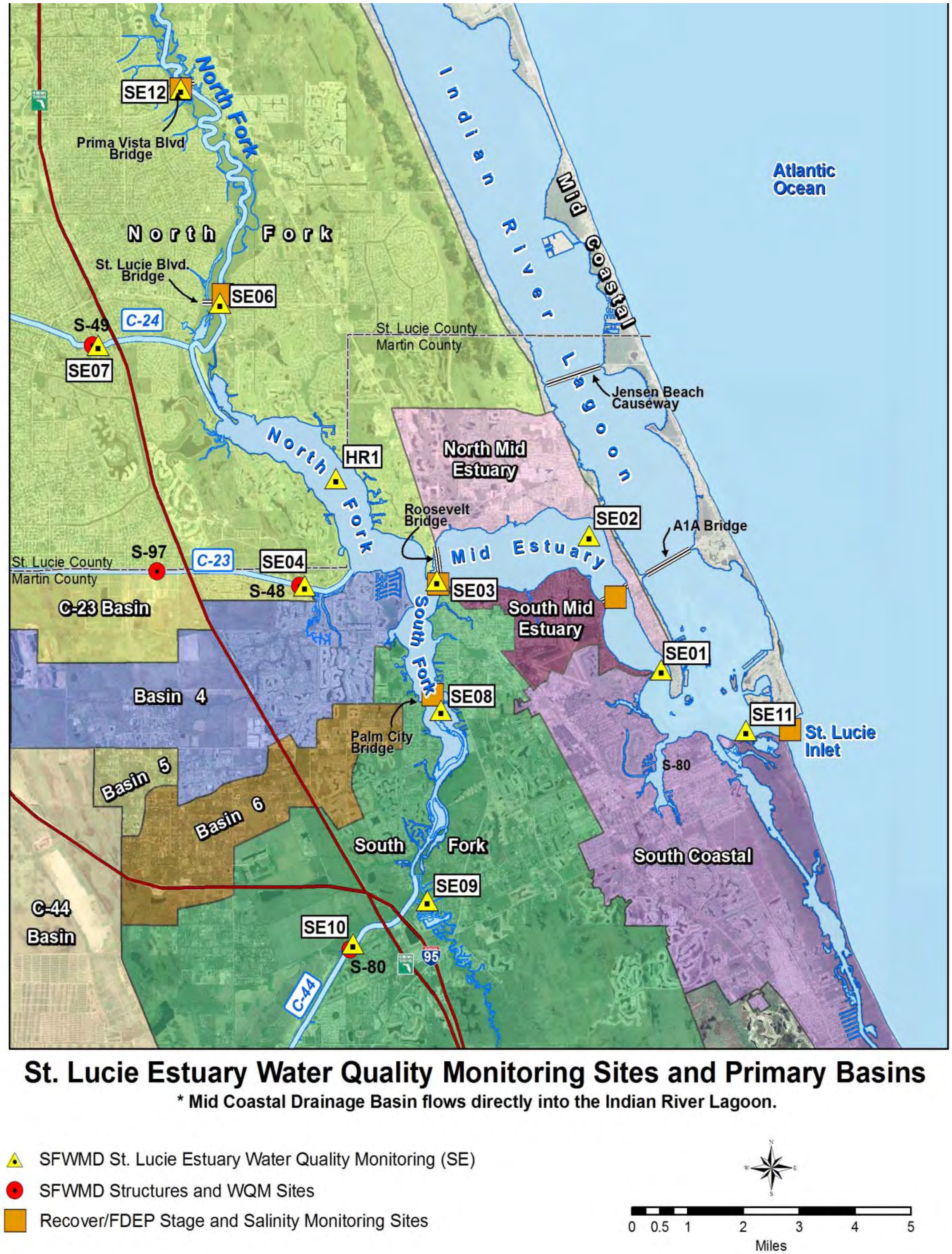


Figure 1. Map showing the St. Lucie River Estuary including the surface water quality monitoring stations and inflow structures

The District has made great efforts and progress in developing numerical hydrodynamic models for the St. Lucie Estuary (SLE). Early hydrodynamic models developed by the District include DYNTRAN, a 1-D hydrodynamic/salinity model (Morris, 1987) and a 2-D hydrodynamic (RMA2) and salinity (RMA4) model (Hu, 2000). Both models have contributed to various studies and projects in the St. Lucie Estuary. Due to the fact that neither of these early models have a water quality component and that SLE is at least partially stratified, the District developed a comprehensive, three-dimensional modeling system for hydrodynamic/salinity, sediment transport and water quality. The CH3D (Curvilinear Hydrodynamics 3 Dimensional) model was developed to simulate the hydrodynamic/salinity and sediment transport of SLE while a standalone water quality model based on EFDC (Environmental Fluid Dynamic Code) was used for simulation of water quality. This report summaries the development, calibration and verification of CH3D hydrodynamic/salinity model for the SLE with data collected for a 9-year period from 1997 to 2005. The water quality model will be documented in a separate report.

The Model Set Up

CH3D Hydrodynamic Model Description

Hydrodynamics are motions of water and forces that drive the water motion. Hydrodynamics is the driving mechanism for the transport of sediments, nutrients, DO and algae and is critical to the understanding of other processes. A hydrodynamic model simulates the water movement providing information including water velocity, circulation pattern, mixing and dispersion, temperature and salinity, to other models such as sediment and water quality models.

CH3D (Curvilinear Hydrodynamics 3 Dimensional) model, originally developed by Sheng (1986) is a non-orthogonal grid model capable of simulating complicated hydrodynamic processes including wind-driven circulation, density-drive circulation and tidal circulation. The non-orthogonal nature of the model enables CH3D to more accurately represent the complex geometry than the orthogonal grid models. The model contains a robust turbulence closure model for accurate simulation of stratified flows in estuaries and lakes. Recent enhancements of the model include modeling of aquatic vegetation, modeling of moving shoreline and addition of sediment transport and water quality models. Coupling of the hydrodynamic model with other modules (sediment transport and water quality) makes CH3D an integrated modeling system capable of simulating complicated estuarine processes. With its efficient numerical scheme and parallel computing technique, CH3D can be a powerful tool to assist water management decisions.

Model Grid

One of the most important features of the CH3D model is its non-orthogonal grid system. The non-orthogonal nature of the model enables CH3D to more accurately represent complex river geometry than its orthogonal grid counterparts such as EFDC. In another word, the CH3D grid can accept the previously developed EFDC grid, at the same time the grid can be refined and aligned to fit the meandering river such as the North Fork

Narrow using CH3D's powerful GUI (Graphic User Interface) system. The new CH3D grid covers the entire estuary of the Southern Indian River Lagoon including St. Lucie Estuary. The grid was further extended for the North Fork Narrow area including the North Fork flood plain (Figure 2). Since the LIDAR data for the floodplain was not available until recently, the modeling work described here does not include simulations of the floodplain, which will be carried out in a later phase study. The CH3D model grid contains 1168 cells with sizes ranging from less than 30 m in the North Fork Narrow to more than 2000 m outside the inlet in the ocean. In the vertical direction, since the model uses sigma coordinate, there are four (4) layers evenly spaced. This should be adequate to simulate vertical stratification.

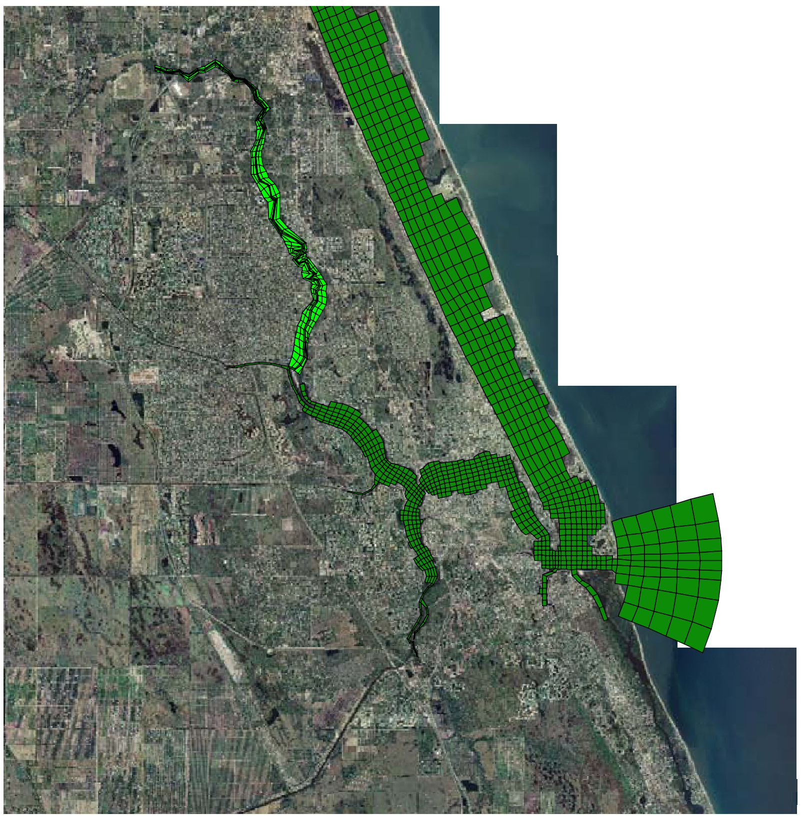


Figure 2. The SLE CH3D model grid

Boundary Conditions, External Forcing

The hydrodynamic/salinity model is driven by external forcing prescribed at the boundaries including tidal forcing at the ocean boundary, freshwater inflow from controlled structures and runoff from the watershed, and meteorological forcing including wind and rainfall. For the SLE hydrodynamic model, boundary conditions include hourly surface elevation at the open boundaries, hourly wind and direct rainfall at the surface based on data from the weather station at Savannas Preserve (SVWX) maintained by the District, daily discharge at the structures including S48, S49, S80, Gordy Road and S50, daily discharge at other non-gauged tributaries that are simulated with the SLE watershed model WaSh (Wan et al., 2003). Inflowing ocean salinity is set at a constant of35 ppt. Tributary salinity is a constant zero (completely fresh).

Tidal boundary conditions

Tides enter the model domain through two inlets: the St. Lucie Inlet and the Ft. Pierce Inlet. In addition, since the model covers only part of the Indian River Lagoon, an open boundary is needed just north of Vero Beach in the IRL. Hourly surface elevations were prescribed at these open boundaries: the ocean boundaries outside the two inlets and the model boundary across the IRL at Vero Beach. For the simulation period from 1997 to 2005, there were observed water level data available. However, significant data gaps exist. The methodology used to fill the missing water level is described below.

The method combines harmonic tide prediction with estimated low-frequency water level. Low-frequency water motion is the motion that has a frequency lower than astronomical tide and can be obtained practically by applying a low-pass filter with a certain cutoff frequency lower than major tide. This methodology takes several steps.

Step 1, harmonic analysis was performed to obtain tidal constituents. Table 1 shows the computed major tidal constituents at the three open boundary sites based on measured water level.

Table 1. Tidal constituents at St. Lucie Inlet, Ft. Pierce Inlet and Vero Beach

Station		M2	S2	N2	K1	O1	K2	P1	Q1	MF	MM
SLE	Amp	0.254	0.036	0.053	0.05	0.04	0.01	0.015	0.008	0.017	0.015
	Phase	27	47	4	234	240	42	228	232	66	78
FPI	Amp	0.30	0.043	0.071	0.057	0.042	0.009	0.02	0.01	0.02	0.008
	Phase	358	39	322	227	209	51	212	189	93	169
Vero	Amp	11.2	0.01	0.02	0.023	0.021	0.005	0.007	0.004	0.014	0.019
	Phase	116	156	94	282	276	139	270	288	82	55

Step 2, the tidal harmonics were used to generate tide for periods of missing data.

Step 3, a low-pass filter with a 48-hour cutoff period was applied to measured hourly water level at the three open boundary sites to obtain low-frequency water level. The same filer was also applied to a remote site where long-term records of hourly water level data are available. This remote site used for this study is Mayport, Jacksonville. Correlation analysis was performed to compute the correlation coefficient between low-frequency water level at Mayport and the three boundary sites. Using the measured data in 1999, the correlation coefficients for the low-frequency motion were found to be 0.81, 0.83 and 0.84 at St. Lucie Inlet, Ft. Pierce Inlet, and Vero Beach, separately.
Step 4, low-frequency water level for the missing data period was estimated using linear regress based on the correlation analysis in Step 3. And finally,

Step 5, the estimated hourly water level for the missing periods was obtained by combining the harmonic tide with the estimated low-frequency water level.

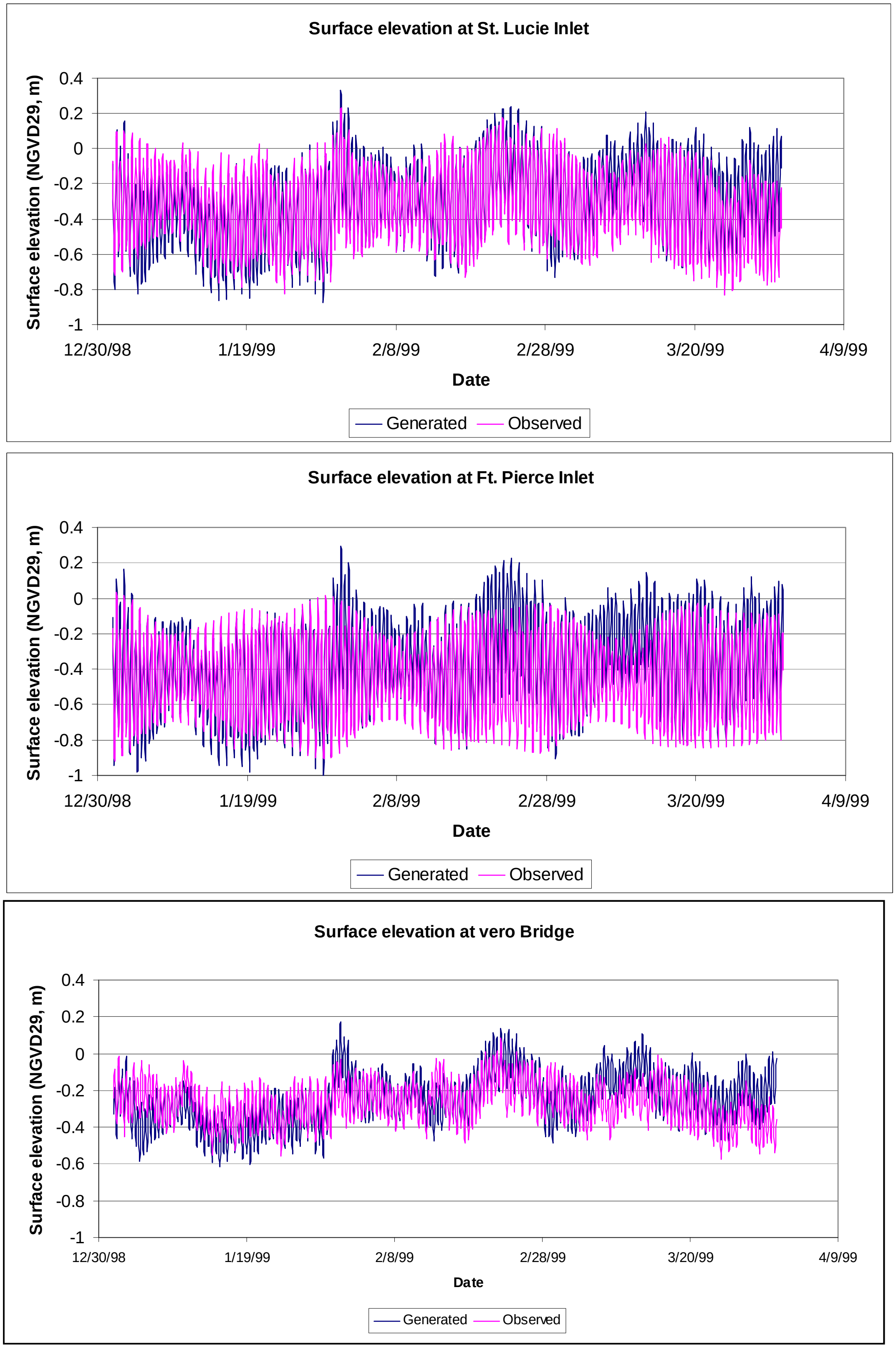


Figure 3. Surface elevation generated by the combination of harmonic tide and low frequency motion compared with observation at three ocean boundary locations: St. Lucie Inlet, Ft. Pierce Inlet and Vero Bridge.

To validate this approach, Figure 3 shows the comparison of water level generated using the above method with observed data during the first three months of 1999 at the three boundary sites. In general, there are good agreements at all three sites

Freshwater inflow

The flow data are obtained from two sources: (1) measured data retrieved from the District DBHYDRO database, including flows through S-48, S-49, S-50, and S-80 (Figure 4) and (2) the WaSh model output in areas not covered by these flow structures. The model outputs include the discharges into St Lucie Estuary from the South Fork, North Fork (Figure 5), Bessey Creek, and Danforth Creek (Figure 5). These daily discharges at flow control structures and from Bessey Creek and Danforth Creek were treated as stream flow into respective model cells. Surface runoff to the tidal North Fork and tital South Fork were treated as distributed flow.

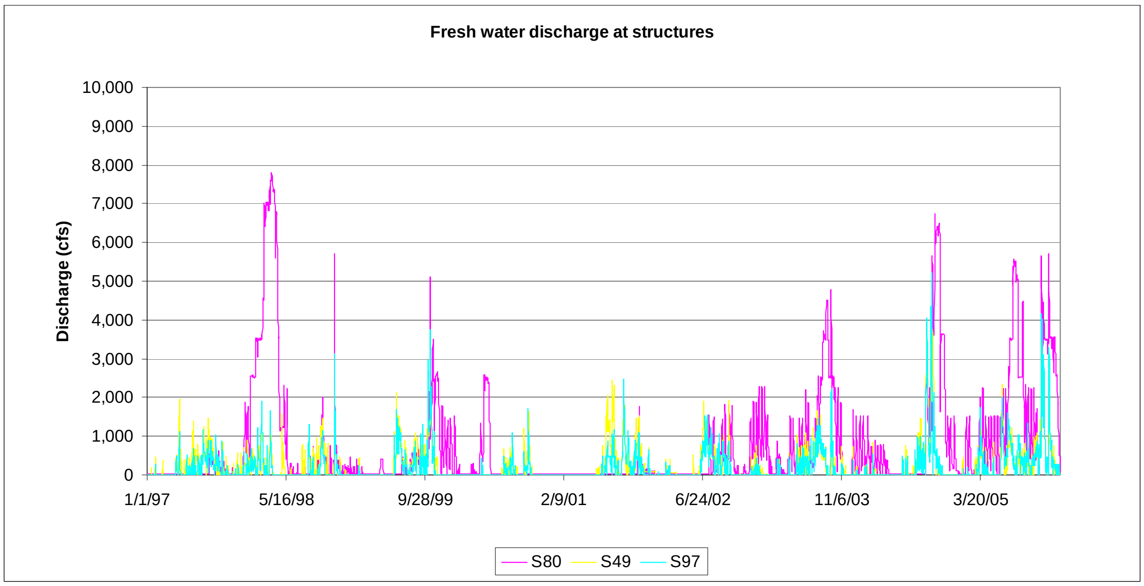


Figure 4. Freshwater discharge at four structures: S49, S97, S80

From the daily flow, the monthly averaged flow, mean annual flow, mean wet season flow, and mean dry season flow during the period of 1997 to 2005 were calculated and presented in Table 3. The total mean annual inflow to SLE is 772,930 ac-ft, of which 76% occurring in the wet season. Figure 6 shows that about 25% of the total inflows comes from C-44 basin, 23% from C-24 basin, 19% from C-23 basin, 22% from North Fork basin, and only 11% from South Fork basin. The two natural stream systems, North Fork and South Fork have a total of 33% flow contribution to the SLE while the other three controlled outflow basins (C-23, C-24 and C-44) account for 67% flow contribution to SLE.

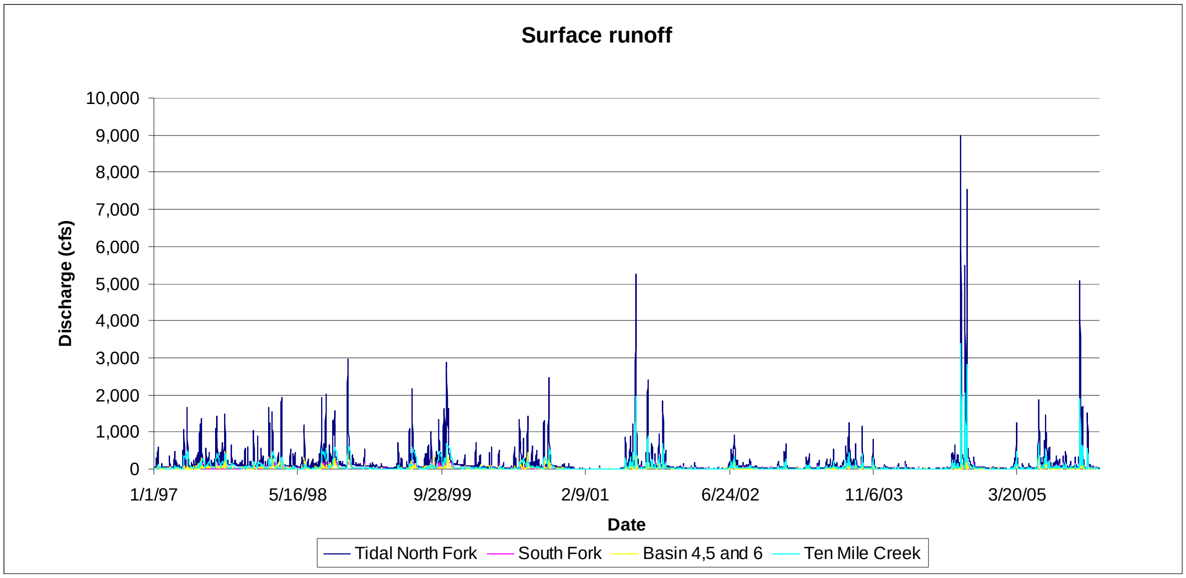


Figure 5. Surface runoff from the tidal North Fork, the South Fork, Bessey Creek, Danforth Creek, and Ten Mile Creek.

Table 2. 1997-2005 Monthly Averaged, Mean Annual, Mean Wet Season, and Mean Dry Season Flow Data (unit: ac-ft)

Month	**S97**	**S49**	**S80**	**North Fork**	**South Fork**
1	2129	4741	6392	4948	3015
2	3815	4415	7855	5792	3394
3	6423	7044	10219	8237	4058
4	2099	3523	4734	3046	2043
5	1150	3143	5636	3814	2109
6	14134	18990	16601	14272	6049
7	17730	24707	19676	15092	6271
8	26212	31848	30769	26500	12183
9	29870	33633	34883	35262	17103
10	30226	31011	33186	32947	15981
11	10979	11784	18003	15039	8003
12	2160	4013	6438	4762	2838
Mean Annual	146927	178853	194392	169711	83047
Mean Wet Season	119321	143332	140752	127887	59698
Mean Dry Season	27605	35521	53640	41824	23350

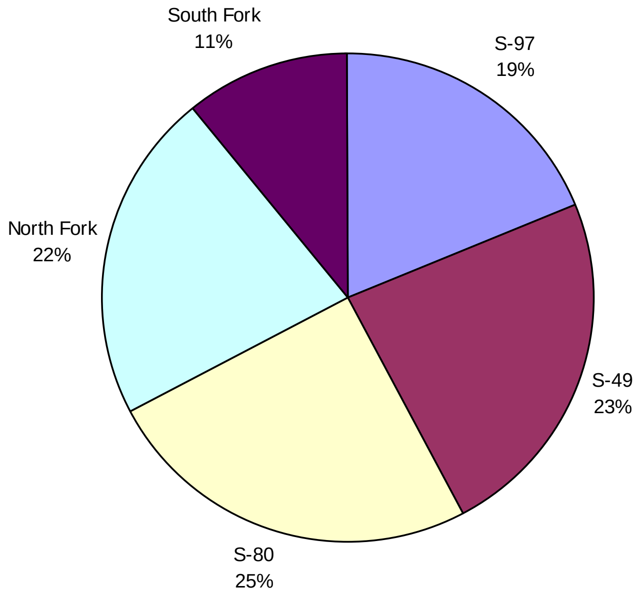


Figure 6. 1997 – 2005 Sub-basin Flow in Percentage to Mean Annual Total Inflow to SLE

Yearly flow for each basin are calculated and presented in Table 4. During the simulation period from 1997 to 2005, Year 2000 represented a dry year and both 2004 and 2005 were wet years due to several landfalls of hurricanes in the watershed.

Table 3. 1997-2005 Annual Flow and Total Annual Flow to SLE (unit: ac-ft)

Year	**S97**	**S50**	**S49**	**S80**	**North Fork**	**North Fork**	**Total Inflow to SLE***
1997	95664	146739	156763	99417	100308	52555	504707
1998	124716	172308	186202	229859	220058	109150	869986
1999	162007	189889	206765	209432	179232	86217	843653
2000	35717	40899	50256	121427	72229	35213	314841
2001	120526	180358	197444	141365	192912	90512	742759
2002	111490	150999	153570	109408	72376	35214	482058
2003	140902	118394	159269	216574	142936	68859	728541
2004	186874	228684	219327	190910	203156	98287	898554
2005	301303	251708	280006	367983	231985	111150	1292428

* Total inflow to SLE is the summation of S-97, S-49, S-80, North Fork, and South Fork flows, and not includes flow from the Lake Okeechobee which is subtracted from the measured flow at S-80. S-50 flow discharges into north coastal instead of SLE.

Model Calibration and Verification

Calibration and Verification Data

The model was calibrated and verified using data collected from District's continuous salinity monitoring sites at A1A Bridge, Roosevelt Bridge (US1 Bridge), Kelstadt Bridge (St. Lucie Blvd Bridge), Prima Vista Bridge, and Midway Bridge and District's monthly water quality monitoring stations (SE01 through SE11).

The continuous monitoring stations measure stage, salinity and temperature at 15 minutes interval. Three salinity monitoring stations A1A Bridge, US1 Bridge and Kelstadt Bridge were started in later 1997. There are two sensors at each of these three sites one for the surface layer and the other for the bottom layer. Prim Vista and Midway were added in 2003. A1A and US1 has the best record among all the sites with few gaps. Kelstadt Bridge has only two years data for 1999 and 2003. Prim Vista and Midway have data available only for 2003. There was no continuous salinity monitoring site in the South Fork during the model simulation period. The Palm City Bridge station data was not available until June of 2007.

Table 4. Summary of data used for the CH3D hydrodynamic/salinity model calibration and verification

Monitoring stations	Monitoring parameter	Data collection interval	Vertical layers	Monitoring period
A1A & US1	Water level, salinity, temperature	15 min	Surface and bottom	Oct 1997 to Dec 2005
Kelstadt	Water level, salinity, temperature	15 min	Surface and bottom	Jan 1999 to Dec 1999 Jan 2003 to Dec 2003
Prim Vista & Midway	Water level, salinity, temperature	15 min	Middle	Jan 2003 to Dec 2003
SE01 to SE04 HR1 SE06 to SE11	Salinity and other water quality parameter	Monthly	Middle	Jan 1997 to Dec 2005

As part of the SWIM initiative a long-term water quality-monitoring program was started in October of 1990 in the SLE. Ten water quality monitoring stations (SE 01, SE 02, SE 03, SE 04, HR1, SE 06, SE 07, SE 08, SE 09 and SE 10) were established to detect long-term spatial and temporal water quality trends in the SLE. In 1997 an eleventh station (SE 11) was added in the St. Lucie inlet to better characterize the water quality values in the estuary (Figure 1). Data were collected bi-weekly from July 1992 through December 1996 and monthly from January 1997 to December 2006. All samples were collected as close to low tide as possible. The monthly water quality monitoring data have a longer and more complete record at all the stations. However they are at a much longer interval comparing to the continuous salinity monitoring stations.

For this study, the CH3D hydrodynamic/salinity model was calibrated and verified mainly on the District's continuous monitoring data including stage and salinity. Salinity data from District's water quality monitoring stations were used to supplement the continuous data set and to expand the spatial coverage. Table 4 summaries the data used for this modeling effort.

In addition to tide and salinity data, current verlocity data collected during the wet season of 2007 were used for model calibration despite that 2007 was not in the main calibration/verification period from 1997 to 2005. Details are given in the section of current velocity calibration.

Calibration and Verification of Tide

Understanding the tidal processes is essential for estuary hydrodynamics. The tidal propagation characteristics in an estuary can be quantified by the astronomical tidal constituents. The major tidal constituents are M2, S2, O1, K1, Q1, P1, K2 and N2. Tidal propagation in an estuary is significantly affected by bottom roughness, which is a primary calibration parameter for a hydrodynamic model.

For the calibration and verification of tidal elevation in the CH3D model, bottom roughness was tuned so that errors for tidal phases and amplitudes were minimized. To achieve this goal, harmonic analysis was performed on surface elevation from model output at District's long-term tide and salinity monitoring stations in the SLE (Figure 1). These stations includes A1A Bridge, US1 Bridge, Veteran's Park, Jensen Beach and South Beach. Stations at Palm City Bridge, Prim Vista Bridge and Midway Bridge were not included due to insufficient measured data during the 1997 to 2005 period.
These harmonics were then compared with known harmonics analyzed from observed data. Tables 5 and 6 show the comparison between observed and modeled, harmonic amplitude and phase of each of the constituents for Year 1999.

Table 5. Tidal amplitudes of harmonic constituents (m)

	A1A		US1		VP		Jensen	
	observed	modeled	observed	modeled	observed	modeled	observed	modeled
M2	0.128	0.145	15	16	0.16	0.16	15	14
S2	0.02	0.02	0.016	0.02	0.02	0.02	0.02	0.02
N2	0.03	0.03	0.025	0.03	0.02	0.02	0.03	0.03
K1	0.04	0.04	0.04	0.04	0.03	0.03	0.04	0.03
O1	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
K2	0.006	0.005	0.006	0.006	0.00	0.004	0.01	0.006
P1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Q1	0.006	0.005	0.005	0.006	0.01	0.01	0.01	0.005
MF	0.03	0.02	0.02	0.02	0.04	0.03	0.03	0.02
MM	0.03	0.02	0.015	0.015	0.02	0.03	0.01	0.01

Table 6. Tidal phases of harmonic constituents (degree)

	A1A		US1		VP		Jensen	
	observed	modeled	observed	modeled	observed	modeled	observed	modeled
M2	76	55	86	63	102	93	335	315
S2	95	70	109	81	105	91	5	334
N2	42	26	65	47	75	58	341	301
K1	265	242	270	261	11	353	241	207
O1	266	239	271	254	274	267	232	214
K2	101	114	105	116	65	41	351	310
P1	271	238	262	232	261	242	251	209
Q1	244	209	271	218	211	171	221	203
MF	52	41	55	41	63	43	37	41
MM	29	354	98	71	163	121	311	327

In addition to tidal constituents, it is equally important to capture low frequency motion of water in an estuary. The low frequency movement is controlled by boundary conditions including low frequency motion at the ocean boundaries as well as freshwater inflow from upstream and meteorological forcing (wind) at the surface. A simple and direct way to show that the model has performed with reasonable accuracy is to compare measured and modeled surface elevation. Table 7 shows the long-term error statistics: root mean square error (RMS) and correlation coefficient (R) between measured and modeled surface elevations.

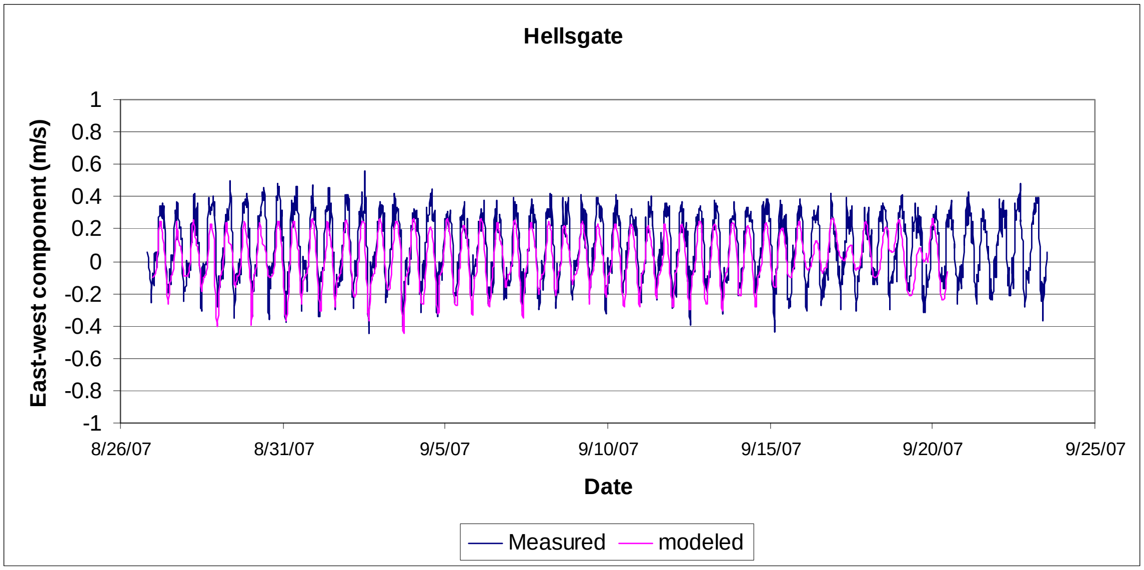
Table 7. Model performance for surface elevation: root mean square (rms) error and R^2 between measured and modeled water level

Station	# of observation	RMS (m)	R^2
A1A	61802	0.07	0.95
US1	66933	0.07	0.95
Kelstadt	40526	0.08	0.94
Prim Vista	17062	0.08	0.93
Midway	16792	0.10	0.90

Considering that there are many data gaps in the ocean boundary conditions, the errors in terms of RMS are well contained and correlation between measured and modeled surface elevation is very good. These statistics show that 1) the tidal boundary conditions were adequate despite large gaps of data and 2) the model has indeed performed well with respect to simulation of tide.

Calibration and Verification of Current Velocities

Currents are the driving force of the transport of salt, sediments and nutrients. It is very important that the model can simulate currents accurately. There are no continuously measured current velocity data available during the simulation period from 1997 to 2005. However, the District deployed five Acoustic Doppler Profilers at five locations in the SLE in August-September 2007 (wet season) and again during May 2008 (dry season). Although neither year is in the simulation period discussed here, the District staff is working to extend the model simulation to 2008. To verify the performance of the hydrodynamic model, simulation for a period of about one month from August 27 to September 24, 2007 is presented and discussed here. For this one-month simulation, no model parameter was adjusted, i.e., the short simulation used the same parameters as in the 9-year simulation run discussed in this report. Necessary changes were made at the open boundaries: observed tidal elevation at St. Lucie Inlet was used at the ocean boundary and gauged freshwater flow at the structures downloaded from DBHYDRO were used at the tributaries. Since there was no WaSh model run for this period, surface runoff from the watershed was estimated in proportion to the gauged flow following statistics shown in Figure 6. Figures 7 to 9 show modeled surface velocities (east-west and north-south components) compared with measured current velocities at Hellsgate, US1, and Kelstadt Bridge stations. The results show very good agreement in general at all three locations. However, there are noticeable discrepancies. Note that the model seems to overestimate the east-west component at US1. This is likely due to the fact that the ADCP was mounted behind the bridge pier, which was not resolved by the model. therefore, the position of this station may not be the idea to represent the currents at US1 since the current velocity was subject to localized restriction by the bridge peir. The second discrepancy is displayed in the north-south velocity component at Hellsgate. Hellsgate is located in between A1A Bridge and SE01. The measured north-south component would suggest a net northward residual flow at this location which is difficult to explain since one would expect exactly the opposite because of the discharges from upstream. This discrepancy needs to be further investigated in a later study.



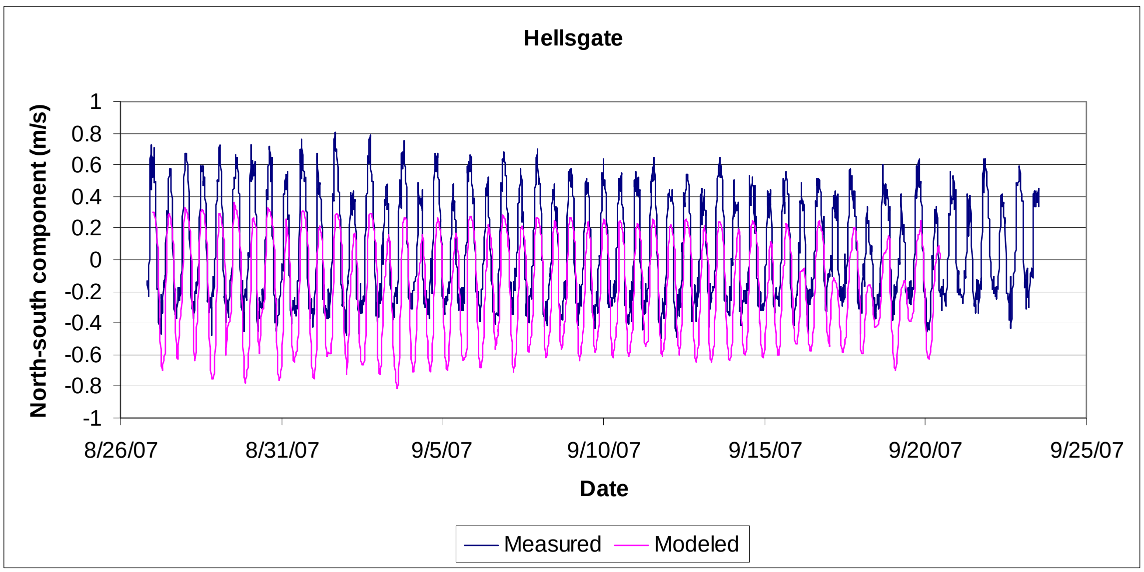


Figure 7. Modeled velocity (red) compared with measured at Hellsgate in August-September, 1997

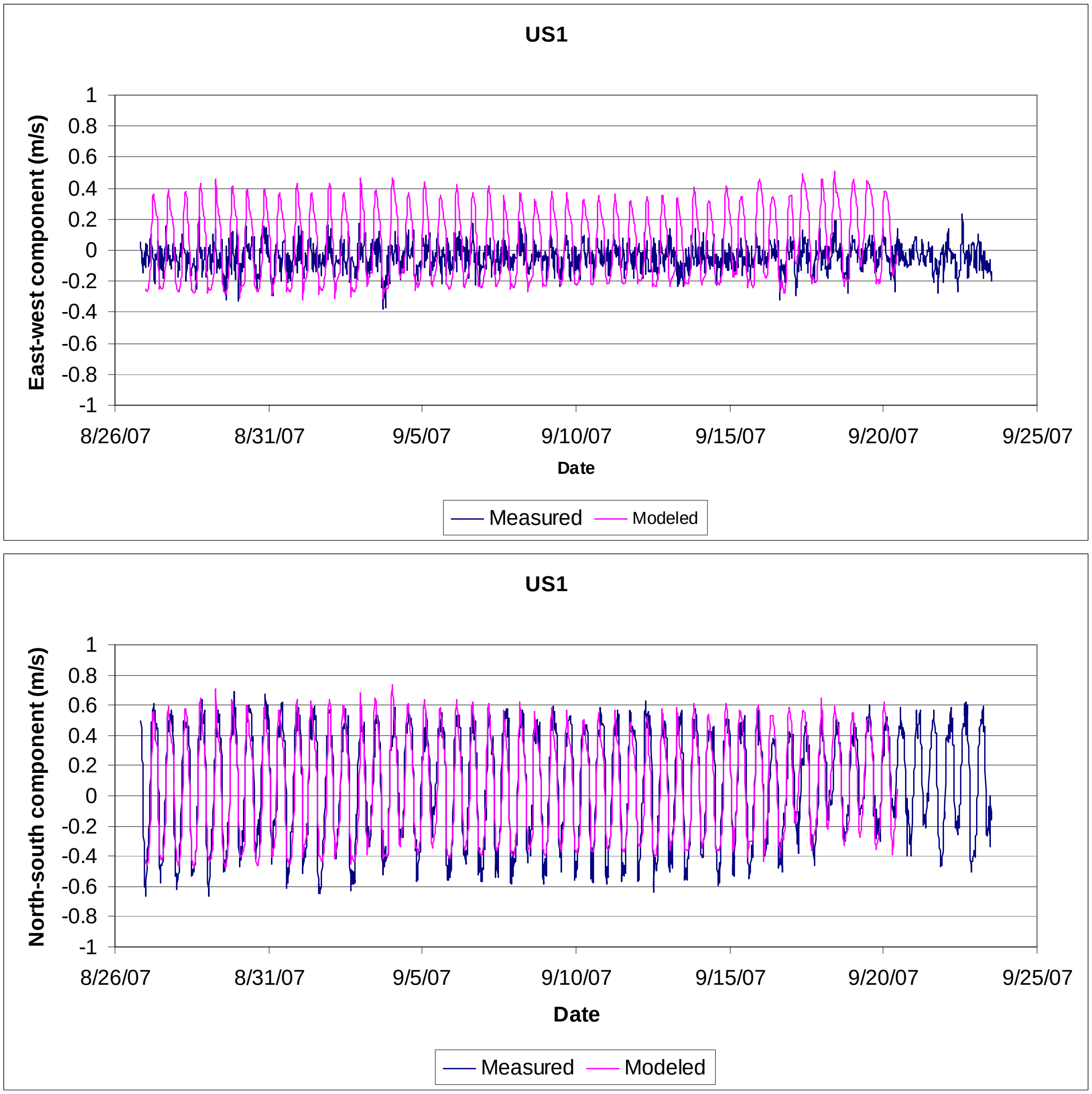


Figure 8. Modeled velocity (red) compared with measured at US1 Bridge in August-September, 1997

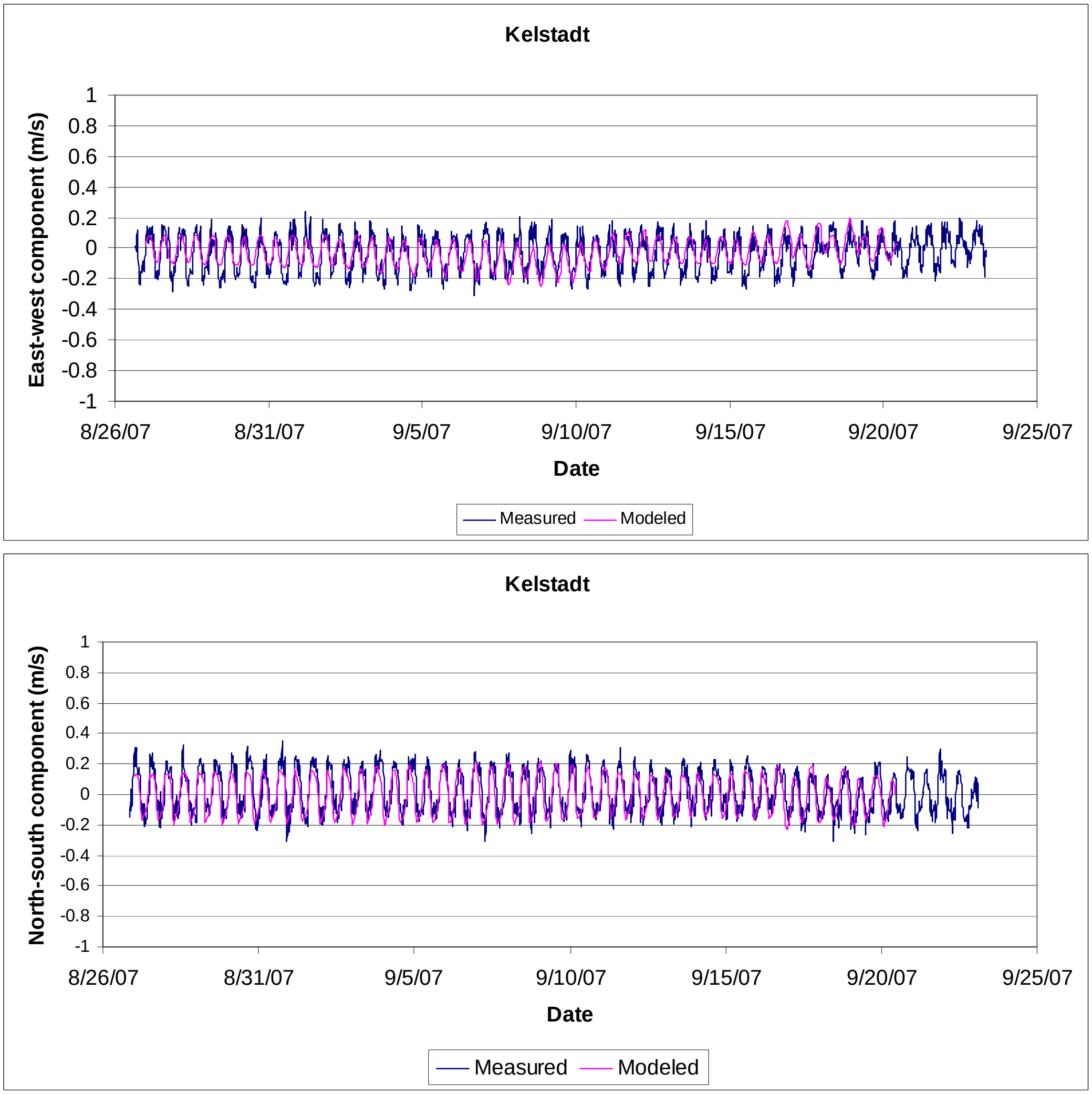


Figure 9. Modeled velocity (red) compared with measured at Kelstadt Bridge in August-September, 1997

Calibration and Verification of Salinity

In an estuary, salinity is largely controlled by freshwater inflow in addition to tide. The accuracy of gauged and un-gauged flow is critical for the simulation of salinity. Fortunately, St. Lucie has long record of gauged flow at structures that show reasonable accuracy with exception that the flow recorded at Gordy Road may sometime be questionable. Therefore, to some extent, the accuracy of the salinity simulation owes its success to the accuracy of the WaSh watershed model. Uncertainties at open boundaries conditions are well known in hydrodynamic/salinity modeling. The approached used by this study is very conventional and used by many other studies (Sheng 1986, Sheng and Davis 2003). At the ocean boundary, for incoming tide, the salinity is prescribed as ocean water salinity, for outgoing tide, a simple upwind (and/or higher order) advection scheme using the following equation:

$$\frac{\partial S_b}{\partial t} + u\frac{S_i - S_b}{\Delta x} = 0$$

Where S_b is the salinity at the open boundary, Si is the salinity at immediate grid cell. Using a constant value for the incoming tide sometimes can be problematic especially for the period when the tide just turned. One way to do it is giving a certain time for the transition of the salinity value goes to become ocean water salinity value. The uncertainty at the boundary is further mitigated by extending the boundary offshore. The question is how far offshore the boundary should be? It depends on the size of the estuary. Salinity results at A1A (Figure 10, Appendix D) clear show the offshore area is adequate for this model.

Salinity is always set to zero at the freshwater entries. It is worth noting that one important factor that may influence salinity results is turbulence. Even for shallow estuaries such as the St. Lucie Estuary, stratification exists during neap or receding tide and when appropriate amount, neither too much nor too little, of freshwater is present in the system. Initial condition for the salinity was interpolated from observation at District's monitoring stations. A spin-up time of approximately one month is needed for the model to reach dynamic equilibrium. The 9-year simulation was performed on District's Linux Cluster. It took about 24 hours using a time step of two minutes. Hourly salinity output was produced and compared with District's salinity monitoring data at A1A, US1, Kelstadt Bridge, Prim Vista Bridge and Midway Bridge (Figures 10 to 12) and District's water quality monitoring stations SE01 through SE11 (Figures 13 to 15). Model results were averaged for Layers 1 and 2 to compare with the upper layer of the measured data. Similarly, Layers 3 and 4 were measured to compare with the bottom layer of the measured data. Table 7 shows the model performance statistics

Table 8. Model performance for salinity: root mean square error (ppt) and R^2 between measured and modeled salinity

Station	# of observation	RMS (ppt)	R^2
A1A upper layer	63031	3.03	0.95
A1A lower layer	64622	3.23	0.92
US1 upper layer	65662	2.42	0.97
US1 lower layer	67973	2.72	0.96
Kelstadt upper layer	41386	2.35	0.84
Kelstadt lower layer	23790	2.41	0.82
Prim Vista	17080	1.81	0.61
Midway	16792	1.32	0.56

These results show very good agreement between the model and observation. Temporally, the simulation period covers a very wide range of hydrologic and hydraulic conditions from the very dry year of 2000 to very wet year of 1998, 2004, and 2005. The model accurately simulated salinity during these periods including the transition from dry to wet or from wet to dry condition. Salinity at many locations shows large variations, a very dynamics system that the model captured very well. Spatially, significant gradients exist from the St. Lucie Inlet to upstream at both the NF and the SF, and the model performed very well to simulate the gradient accurately. In particular, the model predicted salinities at the NF from Prim Vista to Kelstadt Bridge satisfactorily. This makes the model a reliable tool for model applications including the study of low salinity zone, the Ten Mile Creek Adaptive Management, and the IRL water reservation project. For the period from 1998 to 1999, the model under predicted salinity when compared with the measured data. It could be due to accuracy of freshwater inflow data used in the model because the prediction matched well with measured data in the rest of the calibration period

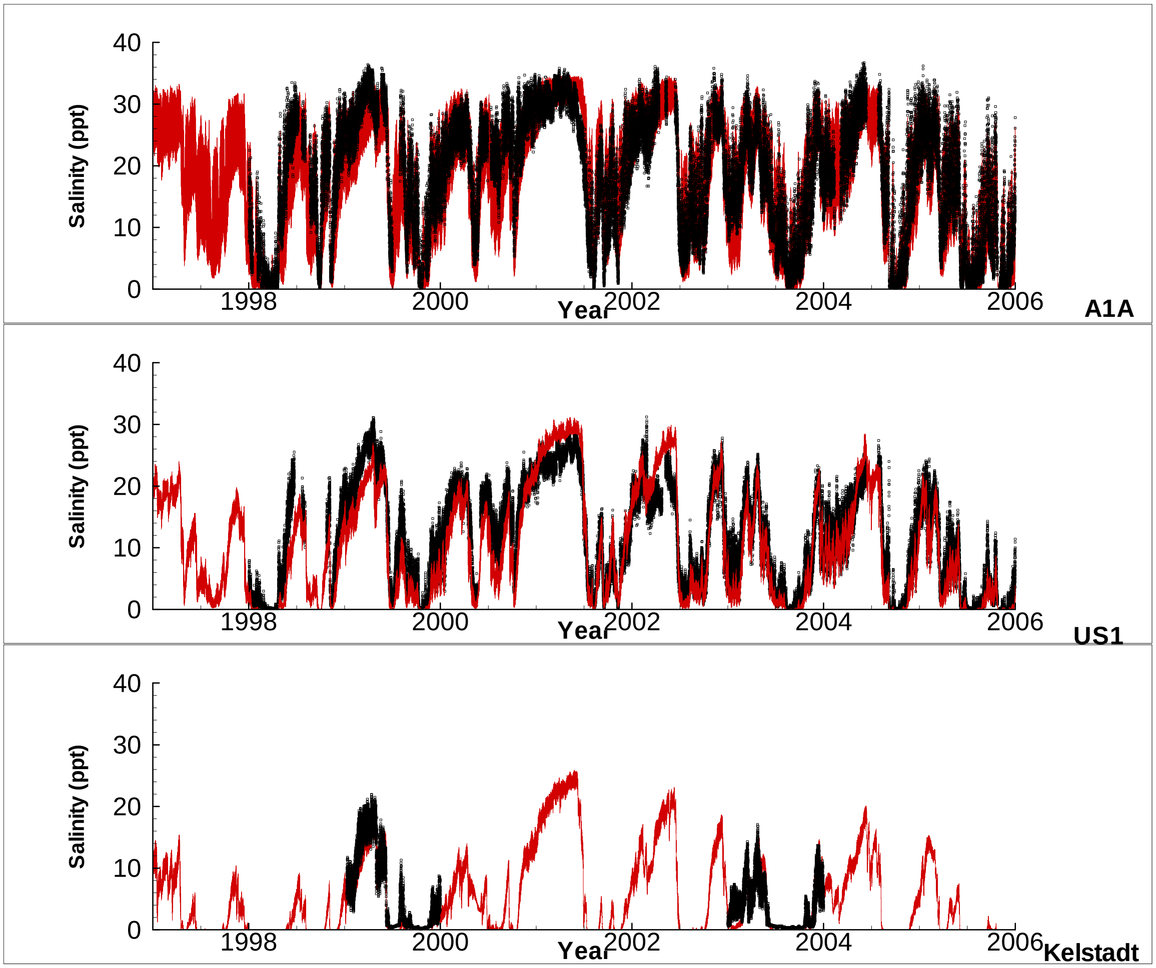


Figure 10. Modeled surface salinity (red) at A1A, US1 and Kelstadt Bridge compared with observation (black) from 1997 to 2005

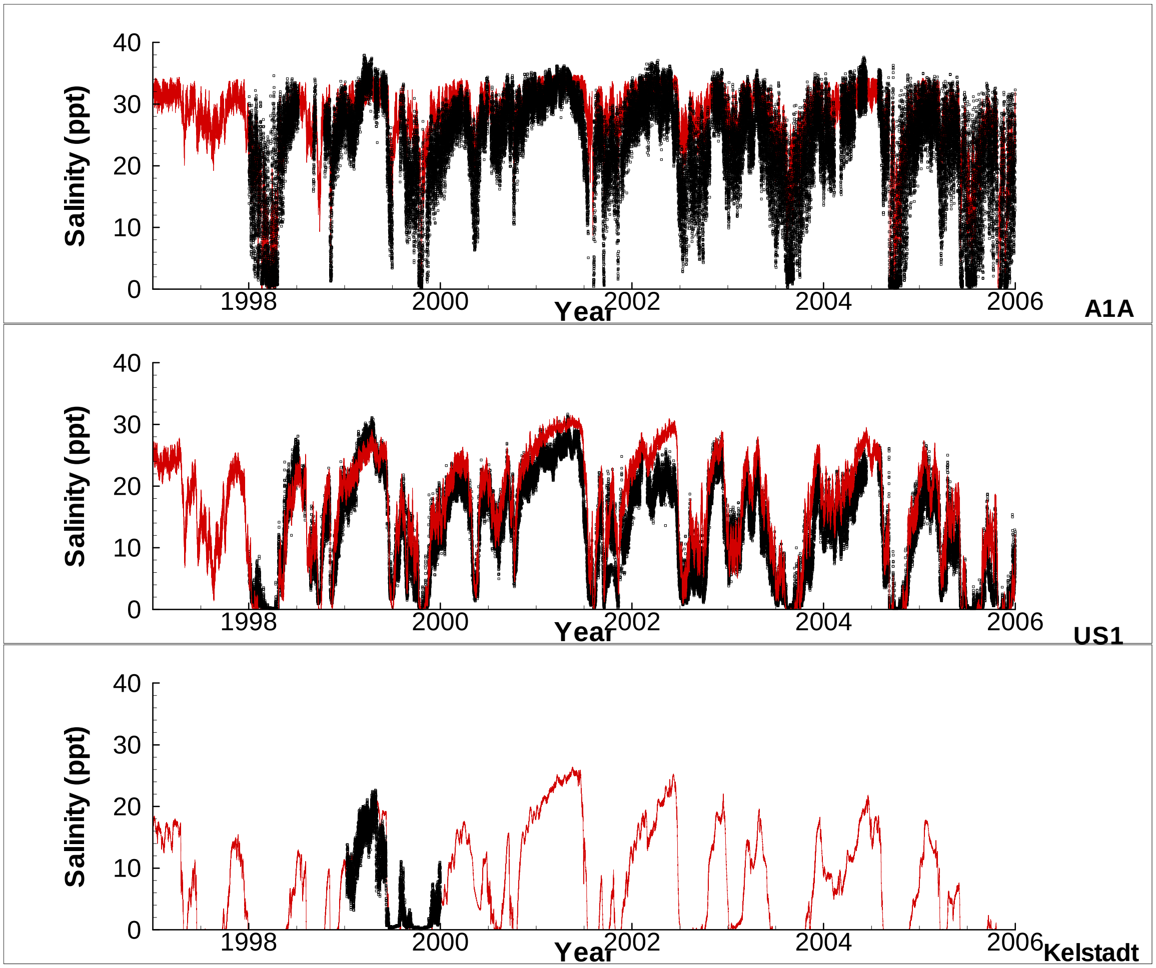


Figure 11. Modeled bottom salinity (red) at A1A, US1 and Kelstadt Bridge compared with observation (black) from 1997 to 2005.

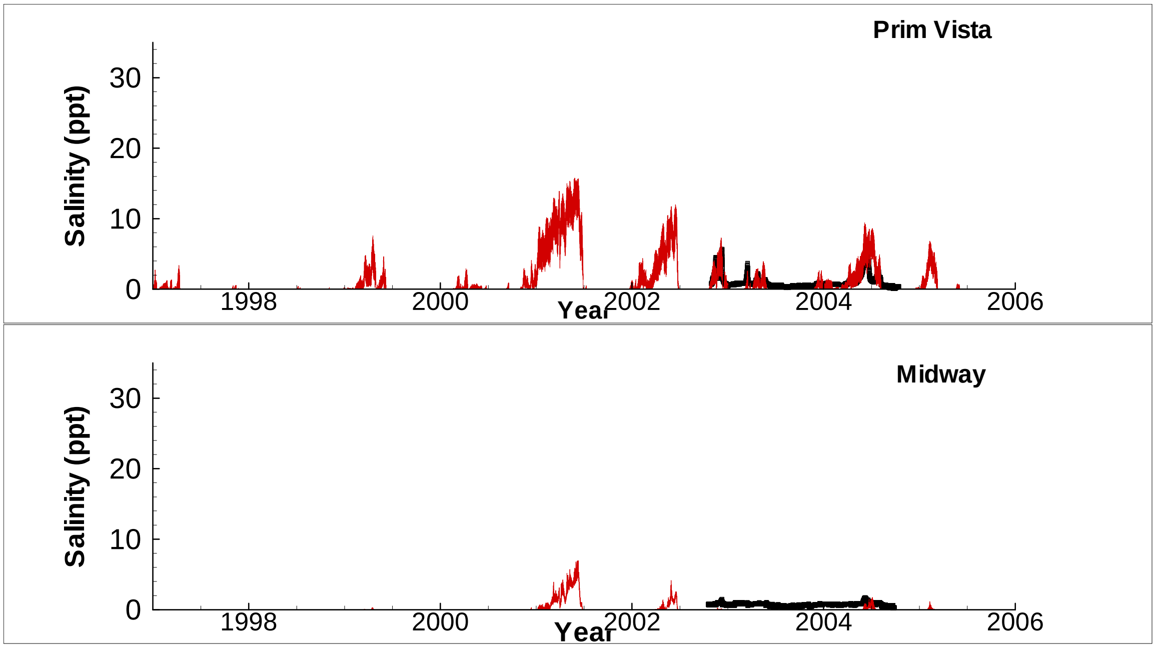


Figure 12. Modeled salinity (red) at Prim Vista Bridge and Midway Bridge compared with observation (black) from 1997 to 2005

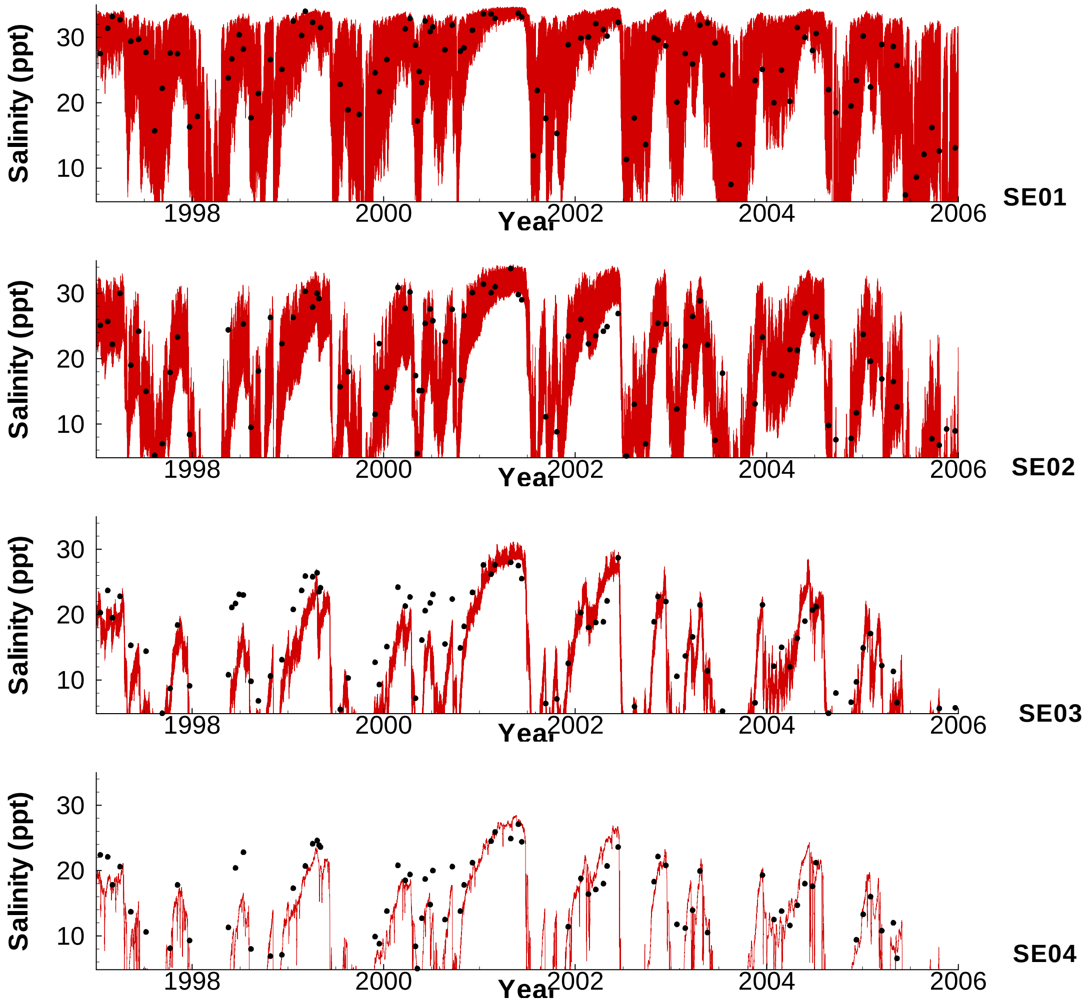


Figure 13. Modeled salinity (red) at SE01 through SE04 compared with observation (black dot) from 1997 to 2005

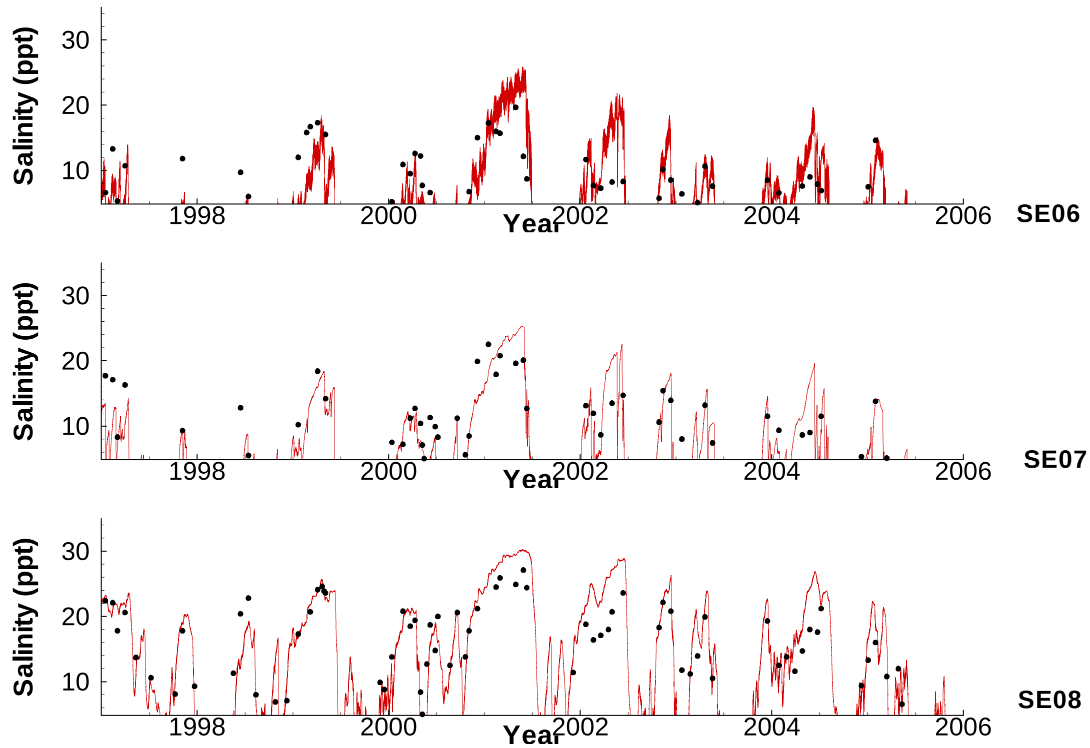


Figure 14. Modeled salinity (red) at SE06 through SE07 compared with observation (black dot) from 1997 to 2005

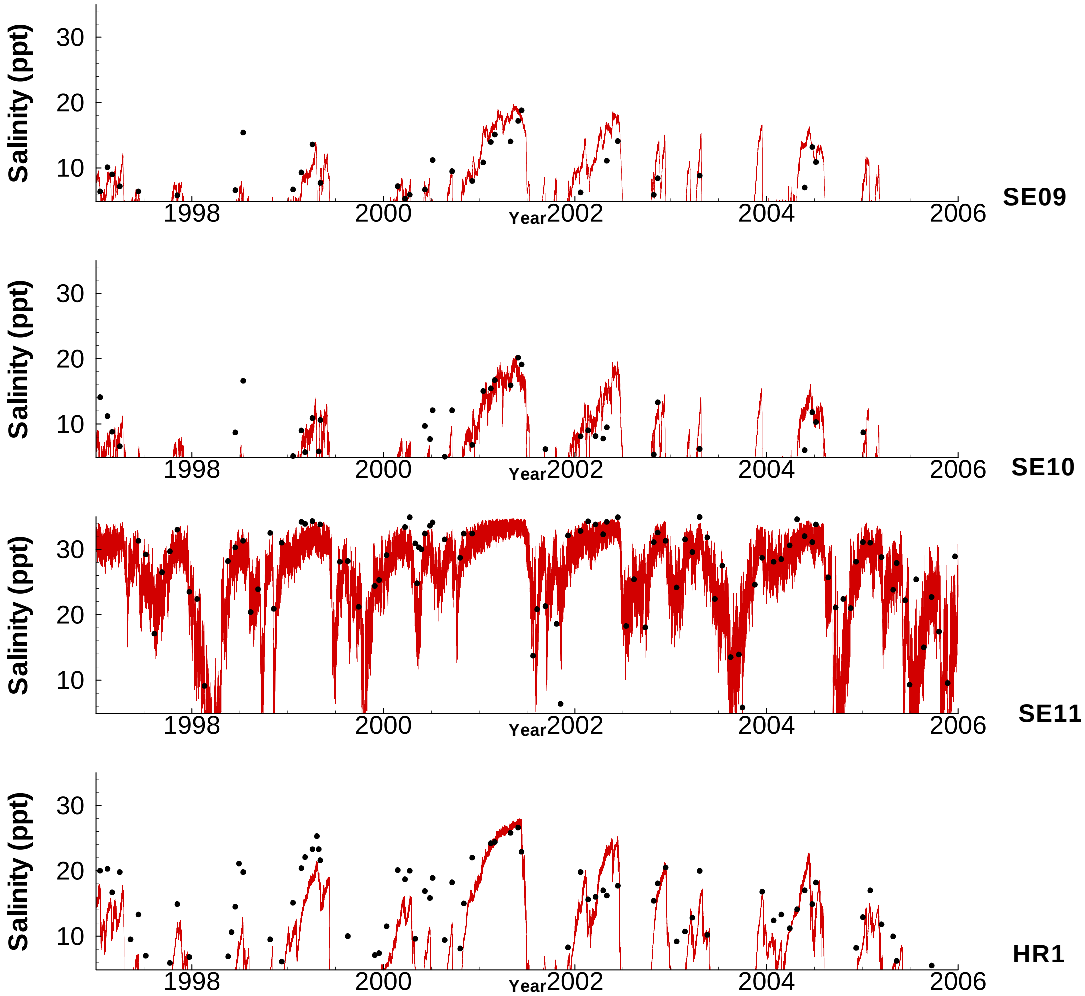


Figure 15. Modeled salinity (red) at SE09 through SE11 and HR1 compared with observation (black dot) from 1997 to 2005

Summary and Conclusions

A hydrodynamic model for the SLE was developed. The model uses non-orthogonal curvilinear grid to represent the estuary consisting of 1168 horizontal cells and four vertical layers. The model was calibrated and verified using observed data from 1997 to 2005. The model was driven by tide at the ocean boundary, freshwater inflow from tributaries and wind at the surface. A methodology was developed to fill the data gaps for the tidal boundary conditions.

For the calibration of tide, error of modeled tidal amplitude was less than 2 cm in the SLE. RMS error for water level was within 10 to 12 percent of tidal range. Current velocity was calibrated using measurements obtained in August-September of 1997. Despite lack of the support of the WaSh watershed model for this period, the modeled tidal currents agree very well at three locations: Hellsgate, US1 Bridge and Kelstadt Bridge.

The model simulated salinity successfully throughout the nine year period which include a wide range of hydrologic and hydraulic conditions and throughout the estuary, in particular the North Fork area, which usually is more challenging than downstream areas. This makes the model a reliable tool for the current water reservation study and other SLE studies and projects.

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Appendix E

Final Report

Early Life History of the Sciaenid Fishes: Emphasis Sand Seatrout in the St. Lucie Estuary

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INTRODUCTION

The Water Resources Development Act (WRDA) of 2000 authorized the Comprehensive Everglades Restoration Plan (CERP) as a framework for modifications and operational changes to the Central and Southern Florida Project, managed by the South Florida Water Management District (District), needed to restore the south Florida ecosystem. Provisions within WRDA 2000 provide for specific authorization for an adaptive assessment and monitoring program. A Monitoring and Assessment Plan (MAP) has been developed as the primary tool to assess the system-wide performance of the CERP by the REstoration, COordination and VERification (RECOVER) program. The MAP presents the monitoring and supporting research needed to measure the responses of the South Florida ecosystem to the CERP.

The MAP also presents the system-wide performance measures representative of the natural and human systems found in South Florida that will be evaluated to help determine the success of CERP. These system-wide performance measures address the response of the South Florida ecosystem that the CERP is explicitly designed to directly affect. A separate Performance Measure Documentation Report being prepared by RECOVER provides the scientific, technical, and legal basis for the performance measures. This work was conducted to examine a perceived and previously documented performance measure that could be used to determine a fish monitoring program could be realistically incorporated into the MAP within CERP.

The fish family Sciaenidae was isolated for study in this survey due to its prevalence in the St. Lucie River ecosystem, ecological and economic value, extensive historical knowledge of specie biology and accessibility during nearly all life history and developmental periods. Bluntly, “if the sciaenids in your system are not doing well, then your system is not doing well.”

The fish family Sciaenidae contains hundreds of species found worldwide in coastal ecosystems and contains many species of great economic and ecological value due to their size, predatory role and relative numbers. There are 21 sciaenid species occurring within the St. Lucie River and within 1-3 miles of the river mouth. At least four of these species have been documented spawning within the St. Lucie River. For this reason the life history of sciaenid fishes, particularly the sand seatrout, *Cynoscion* *arenarius,* silver perch*, Bairdiella chrysoura,* whitemouth croaker*, Micropogonias furnieri* and the spotted seatrout*, Cynoscion nebulosus,* were chosen as potential performance measures for the St. Lucie estuary (SLE).

Life begins for these species in the SLE with aggregate spawning at Hells Gate (Figure) from April to August in high salinity waters. In another MAP project, the underwater sounds produced at Hells Gate are continuously documented and the intensity of sound produced by the sciaenid fishes while spawning has been quantitatively related to the number of eggs spawned. At water temperatures above 25 C trout, silver perch and croaker eggs can hatch in less than 24 hrs. The larvae of all these species are carried by prevailing currents, but also show rheotactic and phototactic migrations based on tidal and diel solar cycles. Most newly hatched sciaenid larvae will stay near objects on the bottom during unfavorable flows and migrate up into the current to be carried passively into favorable feeding and nursery habitats, thus allowing upstream migration in tidal areas that experience substantial flood tides. Nocturnal migrations to the surface to feed are also sciaenid behavioral mechanisms to obtain adequate food for rapid growth (Peebles 1987).

One hypothesis considered here is that larval sciaenids migrate upstream to low salinity nursery waters to utilize abundant prey aggregating at salinity frontal boundaries. They also may seek riverine microhabitats for protection from predators as post larvae. Once in the nursery area, survival of post larvae and juveniles is related to prey availability and predatory mortality. Most post-larval and juvenile sciaenids (and other estuarine fish species) have a broad tolerance of water quality conditions, particularly salinity change, but not their eggs and larvae (Gunter , Alshuth and Gilmore 1994. For this reason the relative abundance of juvenile sciaenids is not necessarily an adequate measure of water quality parameter influence on biota, but numbers of larvae is most certainly an excellent measure of hydrological and hydro-chemical influence on fish (sciaenid survival), thus a good MAP performance measure.

Freshwater inflows into the river and estuary, the North Fork Narrows to the mouth of the river near Hell's Gate, can have a major influence on the presence and availability of prey for larval sciaenids and other important estuarine fish species such as anchovies and gobiids. It also has major impact on the eco-physiological condition of fish larvae. For this reason, the relative success of sciaenid year class in the St. Lucie River was chosen as a performance measure for the quality of estuarine nursery habitat related to inflow management. This project by the South Florida Water Management District (District) quantitatively documented the early life history of the sciaenids and other ecologically important riverine – estuarine species in relation to water quality, prey availability, and other environmental factors from May to August 2007.

OBJECTIVE

The objective of this effort is to obtain, identify and quantify ichthyoplankton and zooplankton samples from the SLE relative to water quality conditions and report the results.

DELIVERABLES

1 – Classification, numbers, densities, developmental stage and size of all fish larval types captured by station, water column position, temporal period and physical parameters.

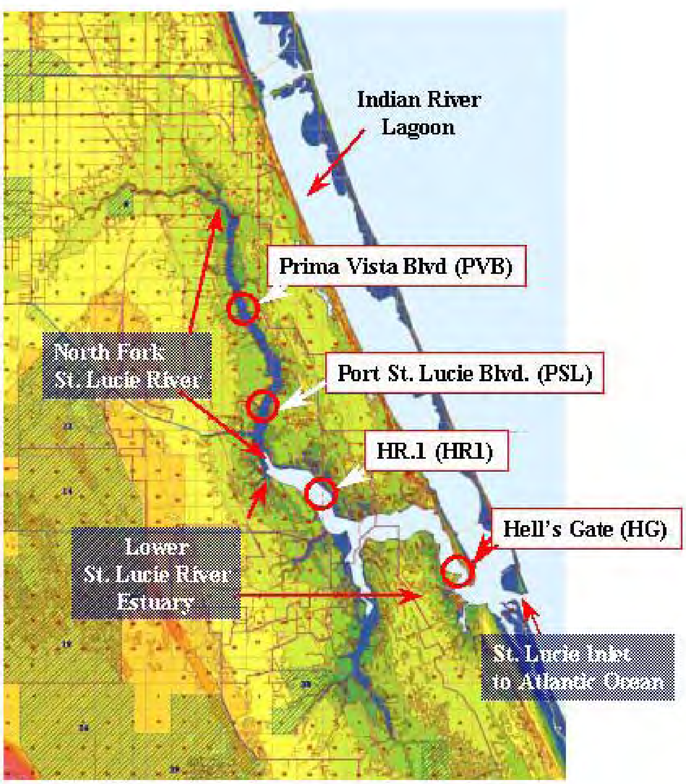
2 – Classification, numbers, densities, developmental stage and size of all copepod adult and larval stages captured by station, water column position, temporal period and physical parameters.

SCOPE OF WORK

A. Sample locations:

Samples will be obtained at four locations in the SLE (Figure): (1) Hells Gate, (2) (2) HR1, (3) Kelstadt Bridge, and (4) Prima Vista Bridge.

Figure 1. Location of plankton collection sites, May 9 through August 14, 2007.



B. Sampling events:

Plankton sampling in the North Fork of the St. Lucie River and the lower River estuary was conducted by four boats simultaneously, two in the North Fork sampling at the Kelstadt Bridge (Port St. Lucie Blvd.) and south of the Prima Vista Blvd bridge while two boats paired to take the downstream collections at the HR1 marker site and at the Hells Gate spawning observatory site. Ten individuals were deployed in these four boats from 1930 to 2430 hrs on each sampling trip. Two people were necessary to take the pump plankton samples, three for the net samples. This required the coordination of various volunteers, ECOS personnel, Florida Oceanographic Society personnel, Jeff Beal of the Florida Fish and Wildlife Conservation Commission and Laura Herren of the Florida Department of Environmental Protection. Six different boats were used for plankton sampling.

The field sampling effort represented a minimum of 40 man hours per trip with some trips requiring 60 man hours, thus approximate average of 50 man hours per trip. There were six trips in total as one practice run was necessary to train volunteers and determine transect location. Therefore, field effort required 300 man hours and an equal amount of time in field prep and post trip equipment treatment, 600 hrs in total.

Five sampling trips were made fortnightly in 2007: May 31, June 14, July 16, 31, and August 14. The planned July 2- 3 trips were delayed and canceled due to unfavorable weather and difficulties in coordinating 10 people and four boats during successive unpredictable cancellations. For this reason the sampling period was extended to August 14. The sampling dates allowed for collections to begin immediately after sunset at mid-flood tide, starting at Hells Gate, moving inland to Prima Vista Bridge. Plankton was collected at all four sample sites on the same evening over a period of 4-6 hrs. At each sample site:

Ichthyoplankton Samples - (1) 0.5 m diameter ichthyoplankton nets (500 micron), with calibrated digital flow meters, were towed for five minutes at about 2 m/sec, twice at the surface and then twice at the bottom for a total of four samples. Boat speed was kept constant at 1,000 rpm throughout the project. Samples were fixed in 10% buffered formalin and labeled. Field records included the GPS position of the boat before and after each tow and current meter readings on the plankton net, time of beginning and ending of the plankton tow and observations of water flow direction (tidal cycle), and any unusual surface conditions, physical and biological. A total of 80 samples were taken between 31 May and 14 August 2007.

Copepod Samples - (2) In addition to the plankton net samples a water pump was used to collect micro- zooplankton twice at the surface and then again twice in bottom waters. The pump effluent for these four samples passed through stacked 210 micron then 80 micron filters producing eight samples. These samples were labeled and fixed in sodium borate-buffered 4% formalin. A total of 160 samples were taken between 31 May and 14 August 2007.

Physical Parameters - (3) a YSI 80 multi-parameter, in-situ water quality instrument was used to measure a vertical profile of salinity, conductivity, pH, dissolved oxygen, and temperature every half meter in depth, including a set of readings just off the bottom, at each sample site before sample collections begin.

D. Sample Identification and Number of Samples

Plankton sorters were trained between 11 June – 15 July and sorting took from 11 June 2007 to 14 January 2008. Plankton net samples were washed in water, filtered and stored in 35% isopropyl alcohol for sorting. Samples were distributed to three part time sorters that were trained in fish larval identification, particularly for target species. Since this project focused on the life history of sciaenid fishes that were known to spawn in the St. Lucie Estuary, particularly those at the fixed acoustic observatories, it was not necessary to process all organisms collected to species, the lowest taxonomic level. The 500 micron net samples were identified as follows: Fish eggs, larvae, and juveniles at least to family, except sciaenids to species when possible. Invertebrates were not identified in the net samples, but were archived in alcohol for future work. Eighty samples were processed at approximately 10 hrs per sample by each of four individuals totaling over 800 hrs in processing time. Single samples contained up to 6,325 fish larvae. Processing time did not include sample monitoring and quality control. It is estimated that well over 1,000 hrs was necessary to sort these very rich and large plankton samples. A total of 44,226 fish larvae, 5,963 eggs, were sorted and archived permanently in 509 labeled jars for future reference and processing.

Ichthyoplankton identification was based on published descriptions of regional species using Richards (2006). An ichthyoplankton identification guide was prepared for all sorters based on literature descriptions. All plankton sorters did remarkably well except one, whose samples had to be processed over again due to miscounts and misidentifications. It is believed that the expertise gained by the sorters in this survey is invaluable if future surveys are to be conducted. They have become familiar with the St. Lucie River ichthyoplankton.

The purpose of collecting pump micro-zooplankton samples is to determine the abundance of Calaniod and Harpacticoid copepods which is the most important prey of young Sciaenid fishes. These 160 samples were archived at the SFWMD.

E. Equipment

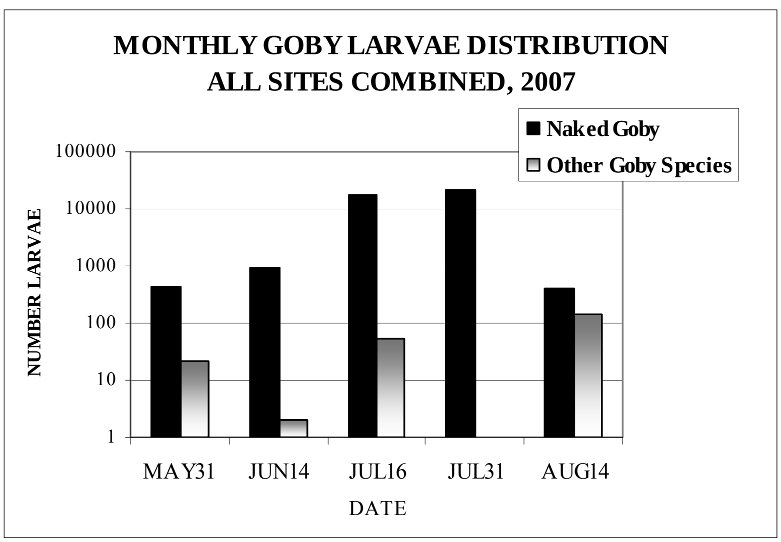
The District provided plankton sampling pumps and associated gear. ECOS furnished the plankton nets, bridles, flow meters, lines and associated tow equipment, water quality meters, sample fixatives, preservatives, and storage materials. Boats were provided by FOS/ECOS collaborative entities from other state agencies (FWC and DEP) and private parties working with FOS and ECOS. ECOS reimbursed all entities for the expense of fuel, boat rental charges ($150 per trip) and other travel costs. ECOS furnished stereo microscopes, dissecting tools and identification materials for sample sorting.

RESULTS

A total of 44,226 fish larvae were sorted into 13 taxonomic categories, most to familial level, but sciaenids, some engraulids, syngnathids, lutjanid and gobiids to species (Appendix Table 1). The most abundant fish was the naked goby, *Gobiosoma bosc*, with 40,567 individuals captured comprising 92% of all larvae collected. Other goby larvae were present including several that do not have published taxonomic descriptions of their larvae. Goby larval verification is still being conducted and since a variety of goby larvae were identified in the samples it is estimated that all fifteen local freshwater-estuarine gobioid species that commonly occur in the St. Lucie River may be identified from these rich samples.

The naked goby lays its eggs on hard substrates with oyster reefs being a favorite oviposition site. Gobies were most abundant at the Port St. Lucie Blvd bridge site in the North Fork of the St. Lucie River, principally during June and July. A huge biomass of invertebrates was also taken at this same site indicating that maximum plankton biomass occurred here when salinities dropped below 10 ppt between June 14 and July 16, the period of the first major rainfall of the year. Similar results occurred during our plankton studies of the Loxahatchee River, May-July 2004.

Figure 2. Temporal distribution of goby larvae in the St. Lucie River, 2007.



Second in abundance were the anchovy larvae (2,883 individuals), most being identified as the bay anchovy, *Anchoa mitchilli*, others as the striped anchovy, *A. hepsetus*. It is possible that *Anchoa cubana*, another common anchovy in this estuary is mixed in with the *A. mitchilli* collections as its larvae greatly resemble A. mitchilli differing slightly in anal fin element counts and vertebral number. The largest anchovy collections were made in May at HR1 in the upper estuary. Anchovies were captured throughout the estuary, mostly in May and June.

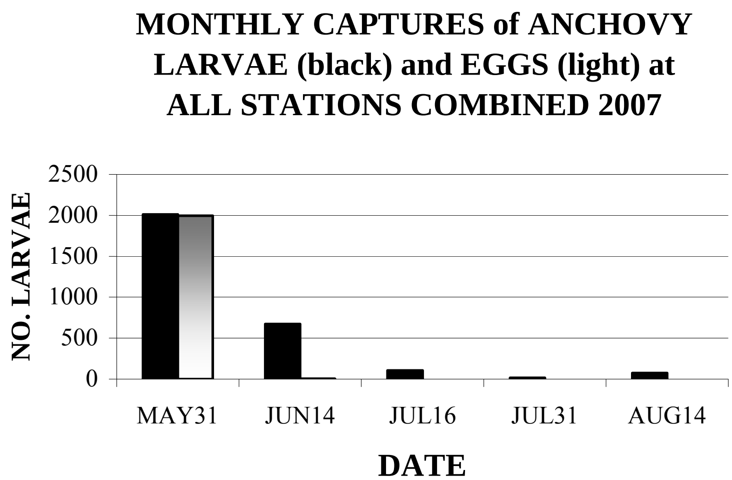


Figure 3 Temporal distribution of anchovy larvae and eggs.

Larvae of the ladyfish, *Elops saurus*, (76 specimens), snook, *Centropomus spp.*, (59 specimens), hogchoker, *Trinectes maculatus*, (37 specimens), and opossum pipefish, *Microphis brachyurus lineatus* (73 specimens) were also captured. These species were significant in that they are fishery species (ladyfish, snook) or of ecological value (hogchoker), or identified as “species of special concern”, the NOAA classification for the opossum pipefish. Larval snook and ladyfish were captured mostly in the North Fork. Snook and ladyfish larvae were more common in July and August during lower salinity periods in the North Fork. In addition, puffers, filefish, a mahogany snapper were identified from the collections by the sorters.

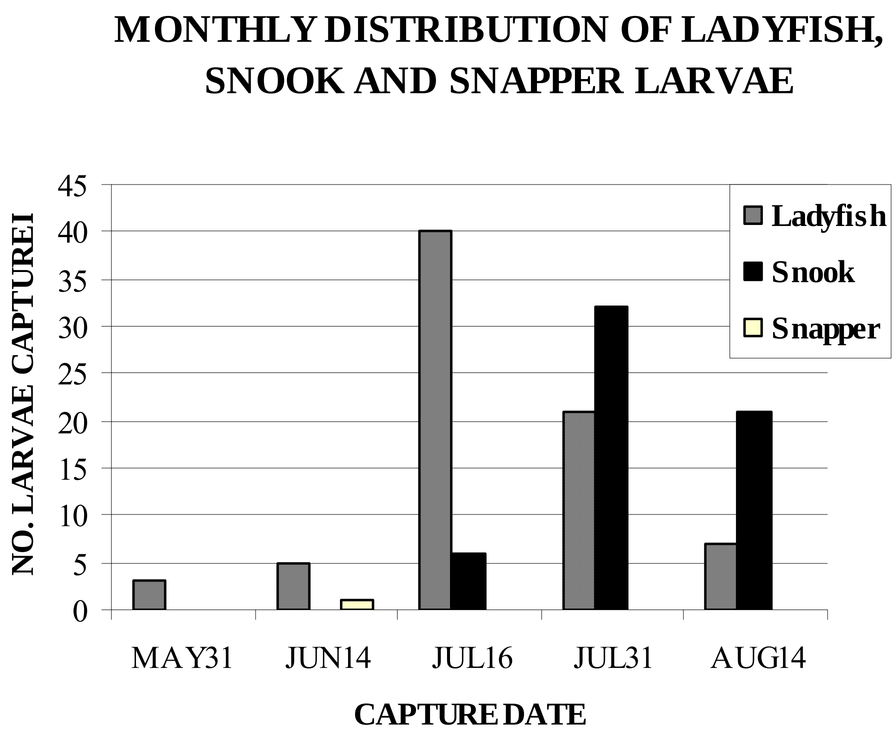


Figure 4. Snook, ladyfish and mahogany snapper temporal distribution.

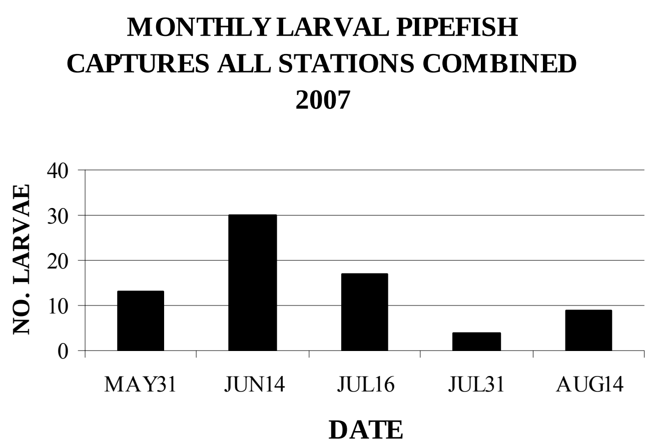


Figure 5. Temporal distribution of larval-post larval pipefish, mostly the opossum pipefish, *Microphis brachyurus lineatus*, a NOAA/NMFS listed species.

The targeted species were sciaenids, silver perch, *Bairdiella chrysoura*, spotted seatrout, *Cynoscion nebulosus*, sand seatrout, *C. arenarius* and the whitemouth croaker, *Micropogonias furnieri*. All but the latter species were captured (Appendix Table 1). Most sciaenid larvae were captured in the estuary, rather than in the North Fork, and most at salinities above 20 ppt May through June. Few sciaenid larvae were captured in late summer collections when salinities were lower, though the spotted seatrout, surprisingly, was the most abundant larval sciaenid in the estuary at HG and HR1 sites from May 31 to July 16. This was in contrast the silver perch dominance of sciaenid larval collections in early and mid May at HG.

	MAY31	JUN14	JUL16	JUL31	AUG14	TOTALS
Silver Perch	12	4	0	7	0	23
Spotted Seatrout	12	18	10	0	0	40
Sand seatrout	0	26	2	0	2	30
TOTALS	24	48	12	7	2	93

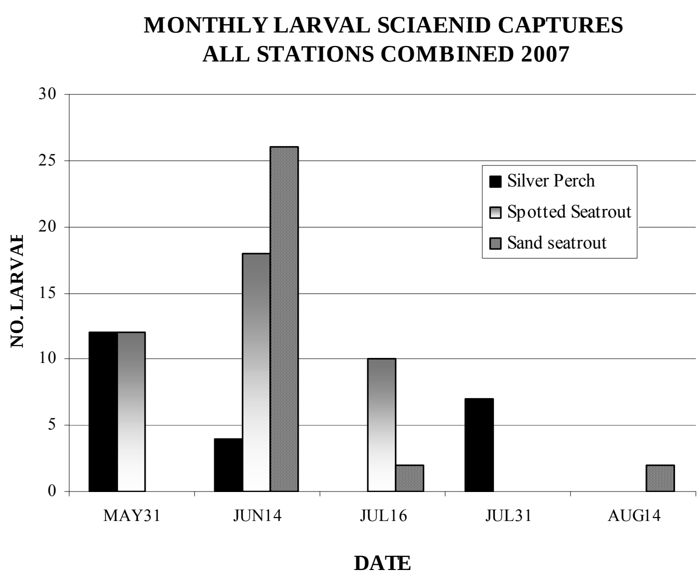


Figure 6. Sciaenid species temporal distribution.

Temporal trend for all larval collections indicates that at least during an extremely dry year, 2007, the beginning of significant rainfall in July coincided with the greatest overall fish larval biomass, in this case mostly gobies. Egg numbers were highest in May and June when salinities were higher. Goby eggs are demersal and therefore, are not captured in towed plankton nets and were obviously present in July based on goby larval abundance. Sciaenid eggs outnumbered all other fish eggs in the plankton and were most abundant in May and June when salinities were higher.

TABLE 1. MONTHLY TOTALS FOR ALL EGGS AND LARVAE CAPTURED IN THE ST. LUCIE RIVER 2007.

	DATE OF CAPTURE					GRAND
	31-May	**14-Jun**	**16-Jul**	**31-Jul**	**14-Aug**	**TOTAL**
EGG COLLECTIONS						
Sciaenid eggs	830	2106	135	1	0	**3072**
Anchoa eggs	1994	2	1	1	0	**1998**
Unidentified eggs	867	22	5	0	0	**894**
Total Eggs	3690	2130	141	2	0	**5963**
LARVAL COLLECTIONS						
SCIAENIDAE	0	0	0	0	0	**0**
Silver Perch	12	4	0	7	0	**23**
Spotted Seatrout	12	18	10	0	0	**40**
Weakfish	0	26	2	0	2	**30**
Croaker	0	0	0	0	0	**0**
ELOPIFORMES (Elops saurus)						
Ladyfish	3	5	40	21	7	**76**
ENGRAULIDAE (Anchoa mitchilli, A. hepsetus, possibly A. cubana)						
Anchovies	2012	672	106	15	73	**2878**
SYNGNATHIDAE (mostly Microphis brachyurus, but also Cosmocampus, Syngnathus)						
Pipefish	13	30	17	4	9	**73**
CENTROPOMIDAE (Centropomus spp., five species)						
Snook	0	0	6	32	21	**59**
LUTJANIDAE (Lutjanus spp., L. mahogani)						
Snapper	0	1	0	0	0	**1**
GOBIOIDS (Eleotridae and Gobiidae, 13 species)						
Naked Goby	434	929	17296	21564	407	**40630**
Other Goby	21	2	52	0	137	**212**
SOLEIDAE (Trinectes maculatus)						
Flounder	0	29	2	3	3	**37**
MONACANTHIDAE (Monacanthus spp. and Stephanolepis spp)						
Filefish	0	2	0	0	0	**2**
TETRAODONTIDAE (Spheroides spp., 4 potential species)						
Puffer	0	2	2	0	0	**4**
UNIDENTIFIED LARVAE	68	112	51	0	0	**231**
TOTAL LARVAE	2456	1782	14804	21653	660	**44296**

SALINITY INFLUENCE ON LARVAL DISTRIBUTION - Salinity is the best indicator of freshwater flow influence on fish abundance of the three physical parameters measured during this survey, salinity (ppt); water temperature (C^o) and dissolved oxygen (ppm).

FIGURE. 7. SURFACE AND BOTTOM SALINITY TEMPORAL PATTERN AT HELLS GATE, SLE, SCIAENID SPAWNING SITE, 2007

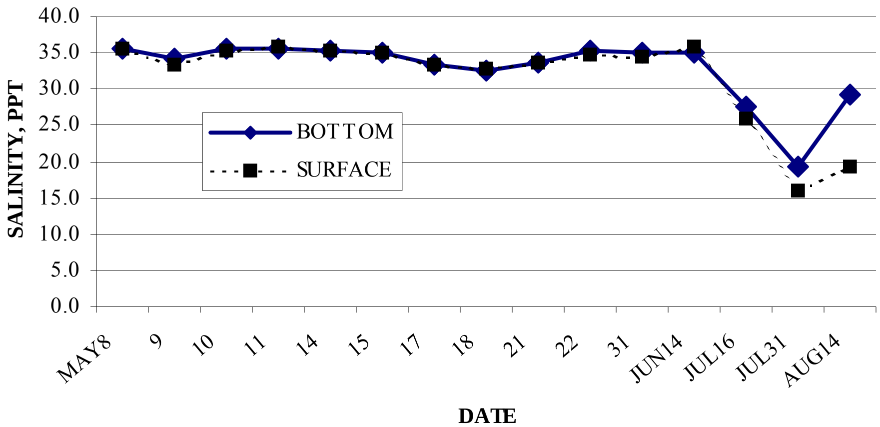
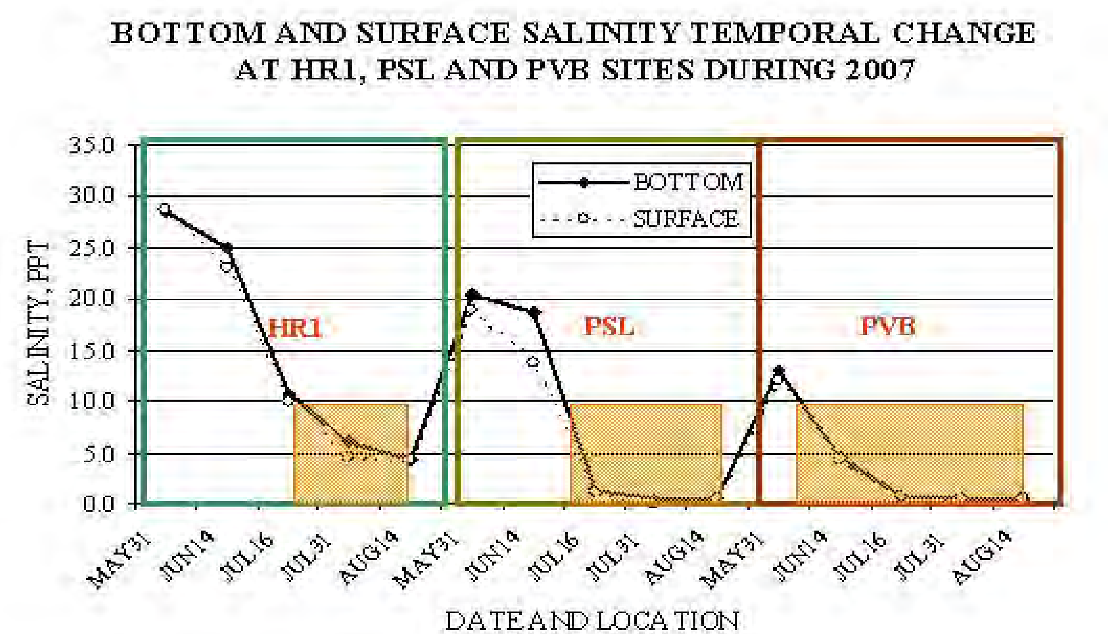


Figure 8. Salinity profiles and temporal trends at HR1, PSL and PVB, 2007.



Bottom and surface salinities at Hells Gate remained above 15 ppt throughout the entire survey period, to August 14 (Figure 7). Salinities remained above 10 ppt at all sites in May, but fell below 10 ppt at PVB in June, in July for the other sites (Figure 8). The colored boxes in Figure 8 depict the salinity window that typically represents the maximum plankton abundance at frontal boundaries. The salinity frontal boundary, maximum salinity change zone, occurred at PSL and this was where the largest ichthyoplankton concentrations were during the 2007 wet season July to August for this survey.

Figure 9. Showing goby larval increase with declining salinity and concentration at the PSL site where the largest spatial change in salinity occurs, the frontal zone.

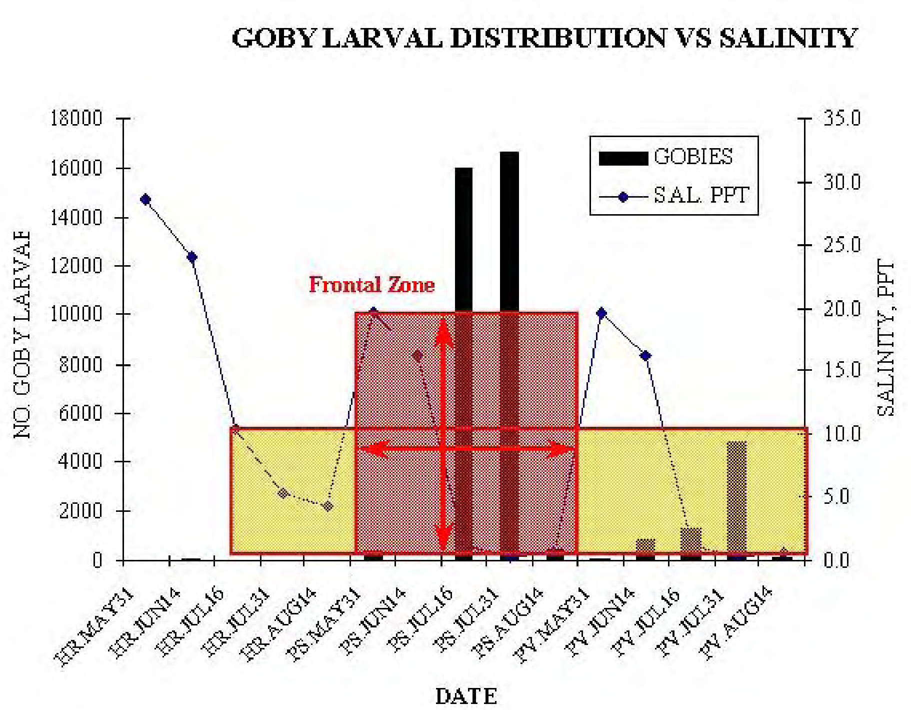
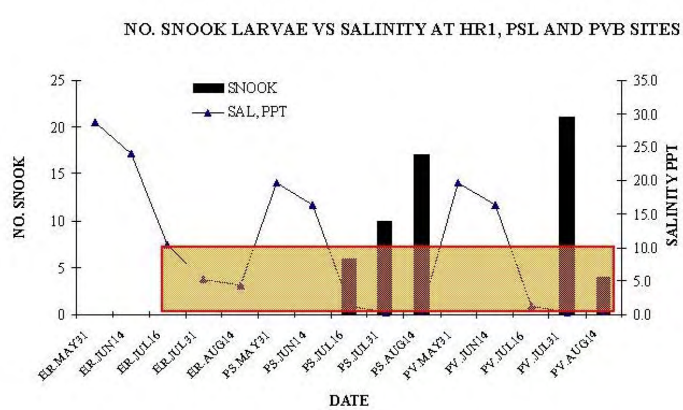


Figure 10. Larval snook distribution relative to salinity.



Sciaenid distribution relative to salinity indicates that sciaenid larvae prefer higher salinities with peak numbers at Hells Gate when salinities were above 30 ppt. Sciaenid egg and larval number dropped significantly at HR1 when salinities went below 15 ppt in July. This agrees with previous studies and field observations of sciaenid egg and larval salinity preference for salinities above 14-15 ppt (Alshuth and Gilmore 1994 for spotted seatrout).

Figure 11. Sciaenid egg distribution at HR1 2007.

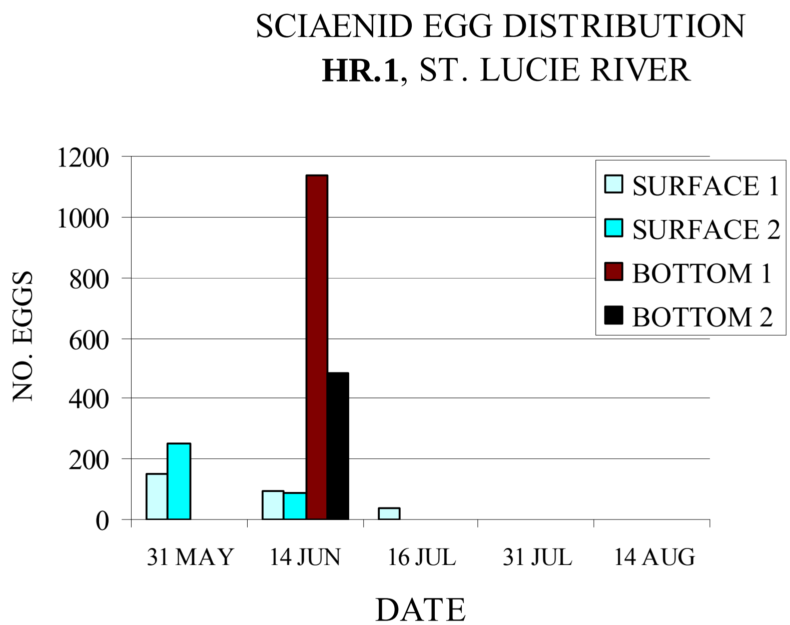
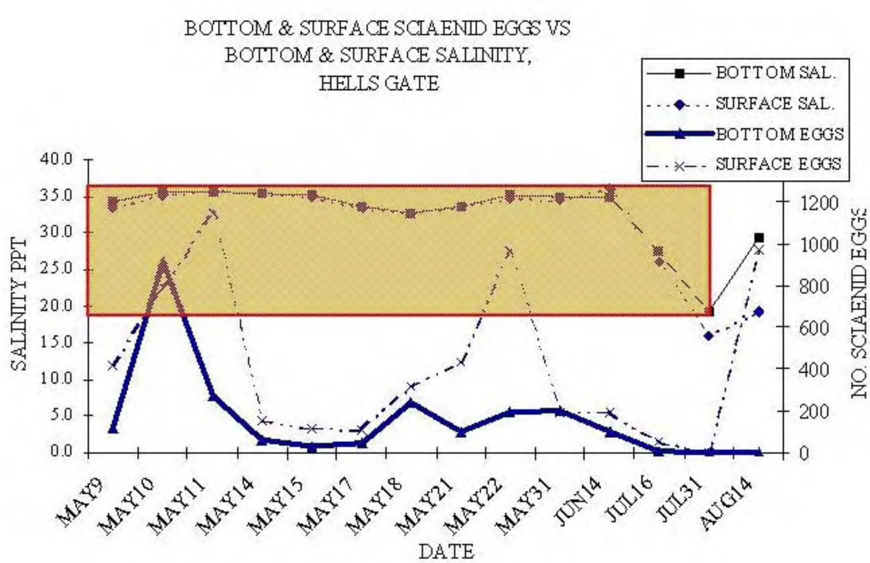


Figure 12. Sciaenid egg distribution relative to salinity at Hells Gate.



Since there were obvious trends in sciaenid spawning activity that were not associated with salinity change during May acoustic observatory sciaenid spawning observations at Hells Gate, care must be taken in making correlations between sciaenid egg and larval abundance and salinity. This was very evident during May when salinities on the bottom and surface changed little at Hells Gate yet sciaenid spawning periodicity changed in a cyclic fashion, possibly on a tidal or lunar cycle (Figures 13 and 14).

Figure 13. Sciaenid egg distribution at HG showing major change in egg numbers during a 3-7 day period.

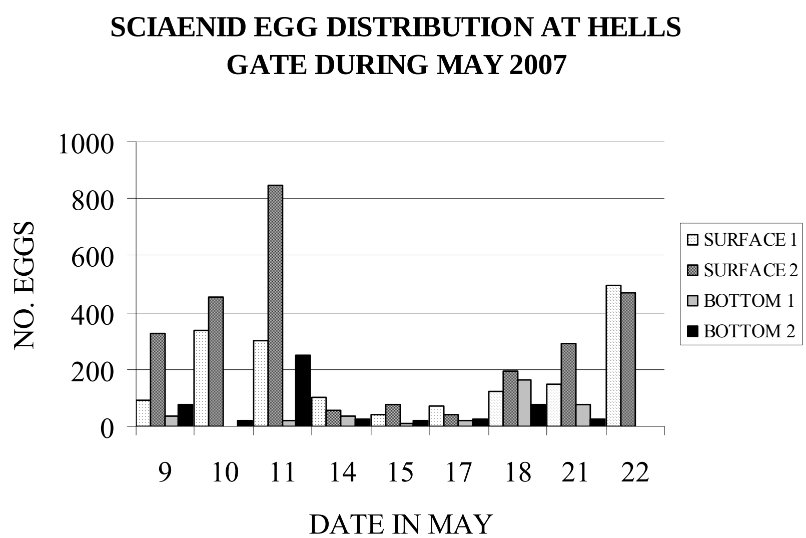
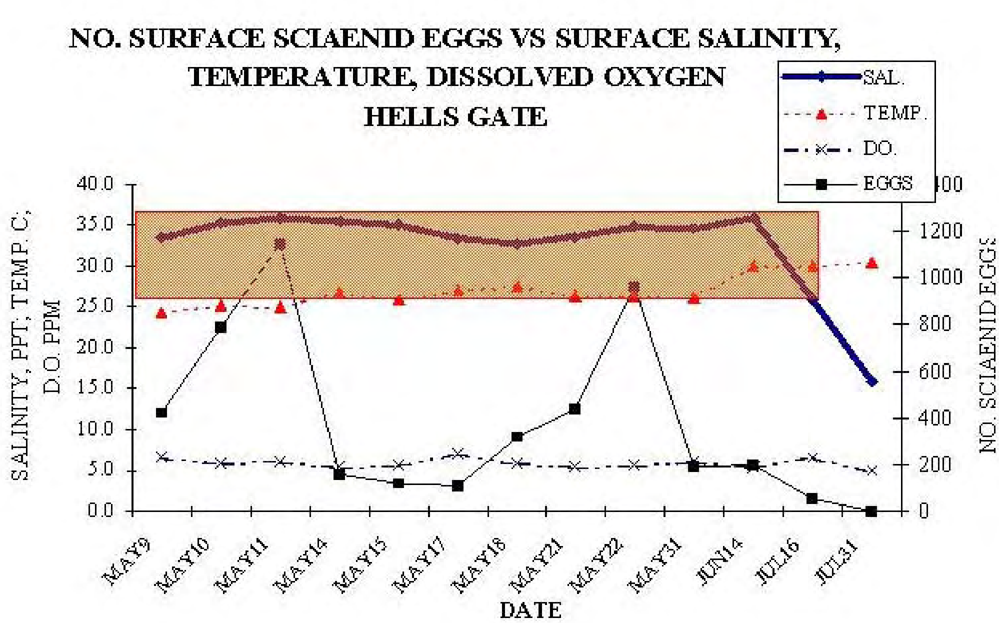


Figure 14. Hells Gate physical parameter variation during the survey period.



SUMMARY

These data reveal preferred sites, periods and physical conditions for fish larvae within the St. Lucie River based on larval and egg collections made from May 9 to August 14, 2007. Sciaenid spawning activity during the survey produced sciaenid egg – larval abundance peaks during May and June while estuarine salinities were high. Sciaenid spawning took place in the lower estuary. This does not preclude the occurrence of large post-larva and early juveniles of all sciaenids near the bottom in the upper estuary of the St. Lucie River. Historical studies have demonstrated a negative association between size and salinity in the sand seatrout, demonstrating that this species utilizes the low salinity portion of Florida estuaries as critical nursery habitat (Peebles 1987). The same is possibly also true for the newly discovered whitemouth croaker, *Micropogonias furnieri*, that is so common in historical samples of adult fish in the St. Lucie River. However, we know nothing of the life history of this species. The silver perch was found as a post-larval juvenile at HR1 in this survey indicating that juveniles of this species may also utilize benthic habitats of the St Lucie River exclusive of the North Fork. It is highly likely that this is the case, as silver perch spawning calls were heard throughout the lower portion of the St. Lucie River from the Roosevelt Bridge south during May 2007. Salinities were above 20 ppt at HR1 until July. Sciaenid eggs dominated the fish egg biomass captured during this survey and sciaenid eggs were most abundant from HR1 to Hells Gate.

The greatest fish larval abundance was in the North Fork of the St. Lucie River at the PSL site. The biomass of invertebrates and fish was greatest in July when local rainfall increased and salinities declined below 10 ppt, forming a frontal boundary at this location. The most numerous fish species at PSL during the time was the oyster substrate associate, the naked goby, and other gobioid species. Next in abundance were the anchovies, mostly the bay anchovy, *A. mitchilli*. Other species well represented in North Fork samples were larval Achirid soles (hogchokers), snook and pipefish. The pipefish consisted mostly of the NOAA/NMFS listed species the opossum pipefish, *Microphis brachyurus lineatus*.

These data indicate that the sciaenids can be used to determine salinity, hydrological and flow impacts on spawning populations in the lower estuary of the St. Lucie River, but not the North Fork of the St. Lucie River. Gobiids, anchovies, possibly snook and opossum pipefish would be better indicators in the North Fork.

The observation of a Critical Salinity Zone (CSZ) at PSL in the North Fork of the St. Lucie River agrees with studies previously conducted in the Loxahatchee River during 2007. This indicates that modeling this zone during the wet season can determine the location and dynamics of the CSZ and thus the location of the large aggregations of fish larvae and planktonic invertebrates. **The health and condition of this larval aggregation is likely to be one of the most important biological conditions influenced by water management in the St. Lucie River.** If future egg and larval sampling is to be used as a CERP monitoring tool and performance measure we suggest using a physical model of the St. Lucie River with timely physical measurements to predict and target

periods of target species larval abundance, during critical spawning periods based on these results. We do not suggest a protocol that requires periodic sampling continuously, nor randomly, as it would take too much effort and expense to do so. Present knowledge can be used to isolate periods of the year and locations within this relatively small riverine system that will generate the largest concentrations of fish eggs and larvae. These periods and sites should be isolated for detailed quantitative information on fish egg – larval abundance relative to hydrological and environmental conditions in the St. Lucie River.

The copepod pump collections have been delivered to the SFWMD for sample analyses relative to these findings.

ACKNOWLEDGEMENTS

This work was conducted with substantial aid from the public and volunteers from the local community surrounding the St. Lucie River and Indian River Lagoon. Plankton sampling was conducted with the aid of six boats from Mark Perry (FOS), Ed Sullivan, Jeff Beal (FWC), Laura Herren (DEP), Phil and Jerry Tafoya, and Heather Hitt. Other volunteers for plankton sampling were Pamela Hopkins, Dick Brown, and Bob Voisenet. Ed Sullivan, Heather Hitt and Pamela Hopkins sorted and identified ichthyoplankton samples.

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Appendix F.
Ichthyoplankton in the North Fork of the St. Lucie Estuary at Three Sites on May 31, June 14, and July 16, 2007

A St. Lucie estuary ichthyoplankton study was conducted during May through July of 2007 at four sites from the inner estuary, low salinity area in North Fork Narrows to the outer estuary at Hell's Gate. One of these four sites was in the middle of the North Fork (HR) and two were located in the Narrows at the Port St. Lucie Bride (PSL) or Kelstadt Bridge and at the Prima Vista Bridge (PVB). On May 31 the salinities at HR, PSL and PVB were about 28, 20 and 13 ppt, respectively, whereas on the following two sample dates (June 14, July 16) the salinities declined to 23, 14 and 4 ppt, and 10, 1 and 0.5 ppt (freshwater). At the highest salinities on May 31, when minimum inflows were occurring, (Table A), ichthyoplankton data from the middle of the North Fork (HR) to the PSL bridge were occupied by eggs from a member of the drum family (Sciaenidae) and the eggs and larvae of anchovies (most likely the bay anchovy). Furthermore, naked goby larvae were present at low densities in the Narrows between PSL to PVB. As inflows increased, the salinities on June 14 at the most upstream station in the Narrows (PVB) fell within the estuarine turbidity maximum (ETM) zone range (0 to 10 ppt), to 4 ppt where the larvae of anchovies, naked gobies, flounder, pipefish (a threatened species) and ladyfish became apparent (Table B). The drum family eggs and many anchovy eggs and larvae, however, remained in salinities greater than 10 ppt. On July 16, all three stations were within the ETM zone range with 1ppt, or the freshwater/saltwater interface, located at PSL. This is the only sampling event to captured plankton at the saltwater interface or presumably at the ETM during this study. Although a paucity of eggs was documented at all three sample sites with the exception of 40 drum eggs at HR, an enormous number of goby larvae were at the PSL saltwater front with decreasing abundance at PVB (Table C). The area at and upstream of 1 ppt from PSL to the PVB was also occupied by pipefish and tarpon larvae. In addition, from a field observation, a huge biomass of invertebrates (presently being processed) was also taken at PSL with the high densities of goby larvae, indicating that maximum plankton biomass occurred in this area during June 14. Overall, results indicated that greatest fish larvae (mostly gobies) and invertebrate abundance was in the North Fork at the PSL (river mile 17.2) when the saltwater front was at that location and freshwater areas were occupied by other recreational and ecologically important fishes.

Table A. Ichthyoplankton in the North Fork of the St. Lucie Estuary at three sites on May 31, 2007.

	DISCARD					DISCARD				DISCARD		TYPE 1	
	31-May	31-May	31-May	31-May	31-May	31-May	31-May	31-May	31-May	31-May	31-May	31-May	TOTALS
Eggs	**HR,B1**	**HR,B2**	**HR,S1**	**HR,S2**	**PSL,B1**	**PSL,B2**	**PSL,S1**	**PSL,S2**	**PVB,B1**	**PVB,B2**	**PVB,S1**	**PVB,S2**	
Sciaen. eggs			151	254				32					437
Anchoa eggs		639	378	659	29		289						1994
Unidentified eggs								865			1	1	867
Total Eggs		639	529	913	29		289	897	0		1	1	3298
Larvae													0
Silver Perch													0
potted Seatrout				12									12
Weakfish													0
Croaker													0
ovies/Herring?			1011	445	137		216	33	3		7	7	1859
Puffer													0
Naked Goby								371	7		30	26	434
Other Goby				3	2						9	7	21
Snapper													0
Pipefish							2	4	1		4		11
Seahorse													0
Flounder													0
Filefish													0
Tarpon													0
Ladyfish				1									1
Snook													0
All Others								2					2
Total Larvae		0	1011	461	139		218	410	11		50	40	2340

Table B. Ichthyoplankton in the North Fork of the St. Lucie Estuary at three sites on June 14, 2007.

	14-Jun	**14-Jun**	**14-Jun**	**14-Jun**	**14-Jun**	**14-Jun**	**14-Jun**	**14-Jun**	**14-Jun**	**14-Jun**	**14-Jun**	**14-Jun**	**TOTALS**
Eggs	**HR,B1**	**HR,B2**	**HR,S1**	**HR,S2**	**PSL,B1**	**PSL,B2**	**PSL,S1**	**PSL,S2**	**PVB,B1**	**PVB,B2**	**PVB,S1**	**PVB,S2**	
Sciaen. eggs	1140	483	97	89									**1809**
Anchoa eggs													**0**
Unidentified eggs									1		1		**2**
Total Eggs	1140	483	97	89	0	0	0	**0**	**1**	**0**	1	**0**	**1811**
Larvae													**0**
Silver Perch		2											**2**
Spotted Seatrout	8												**8**
Weakfish	4												**4**
Croaker													**0**
Anchovies/Herring?	151	162	13	10	13	29	2	1	52	87	19	**58**	**597**
Puffer													**0**
Naked Goby	24	20		3				3	228	232	238	**170**	**918**
Other Goby										1		**1**	**2**
Snapper													**0**
Pipefish			1						3	3	5	**8**	**20**
Seahorse													**0**
Flounder									6	5	1	**2**	**14**
Filefish													**0**
Tarpon													**0**
Ladyfish										1	1	**3**	**5**
Snook													**0**
All Others	9	14	9	2			11					**31**	**76**
Total Larvae	**196**	**198**	**23**	**15**	**13**	**29**	**13**	**4**	**239**	**329**	**264**	**273**	**1596**

Table C. Ichthyoplankton in the North Fork of the St. Lucie Estuary at three sites on July 16, 2007.

	16-Jul	16-Jul	16-Jul	16-Jul		16-Jul	16-Jul	16-Jul	16-Jul		16-Jul	16-Jul	16-Jul	16-Jul		
Eggs	**HR,B1**	**HR,B2**	**HR,S1**	**HR,S2**		**PSL,B1**	**PSL,B2**	**PSL,S1**	**PSL,S2**		**PVB,B1**	**PVB,B2**	**PVB,S1**	**PVB,S2**		TOTALS
Sciaen. eggs			40								1	0				135
Anchoa eggs																1
Unidentified eggs																5
Total Eggs	**0**	**0**	**40**	**0**		**0**	**0**	**0**	**0**		**1**	0	**0**	**0**		141
Larvae																0
Silver Perch																0
Spotted Seatrout																10
Weakfish																2
Croaker																0
Anchovies/Herring?			2					3	4		4	13	18	13		106
Puffer			1													2
Naked Goby			2			3515	4918	2770	4843		366	464	223	191		17296
Other Goby		3				2	5				20	18	4			52
Snapper																0
Pipefish			1				1	1	2		3	5	2	2		17
Seahorse																0
Flounder			1											1		2
Filefish																0
Tarpon		1	1			3	5	2	4		12	2	10			40
Ladyfish																0
Silversides									6							6
All Others			25				6		2							51
Total Larvae	**0**	**4**	**33**	**0**		**3520**	**4935**		**4857**		**405**	**502**	**257**	**207**		14804

Appendix G.
Invertebrate Zooplankton Species Captured from the North Fork of the St. Lucie River and Downstream St. Lucie Estuary from May to August 2007

Table G.1. List of invertebrate zooplankton species captured from the North Fork of the St. Lucie River and downstream St. Lucie Estuary from May to August 2007.

	Zooplankton Species				Species Abundance by Collection Date					
					31.MAY	14.JUNE	16.JULY	31.JULY	14.AUG	TOTALS
1	HYDROMEDUSAE				128	414	1		2	545
2	POLYCHAETE	AUTOLYTUS spp			1					1
4	POLYCHAETE	*EGG MASS*				764				764
5	EUHIRUNDINEA								48	48
6	CHAETOGNATHS				884	664	50	20	16	1,634
7	BIVALVA	MACTRIDAE	*Mulinia*	*lateralis*			128			128
8	BIVALVA	SOLECURTIDAE	*Tagelus*	*divisus*			96			96
9	GASTROPODA	HYDROBIIDAE		*Unident.*					18416	18,416
10	SIPUNCULA					4				4
11	MEROSTOMATA	LIMALDAE	*Limulus*	*spp.*		8	4			12
12	CLADOCERA	ONYCHOPODA	*Pododon*	*sp.#1*					286608	286,608
13	CLADOCERA	ONYCHOPODA	*Pododon*	*sp.#2*					6320	6,320
14	OSTRACODA		*Unident.*						33	33
15	OSTRACODA		*Delphnia*	*spp*		132	64			196
16	CALANOIDA		*Centropages*	*typicus*		292				292
17	CALANOIDA		*Lapidocera*	*aestiva*	190	224		32		446
18	CALANOIDA		*Pseudodiaptomus*	*pelagicus*		1979	1562	3646		7,187
19	CALANOIDA		*Parvocalanus*	*crassirostris*	200	768				968
20	CALANOIDA		*Paracalanus*	*parvus*		416				416
21	CALANOIDA		*Temora*	*turbinata*		336				336
22	CALANOIDA		*Unident.*				192		2114	2,306
23	POECILOSTOMATOIDA		*Corycaeus*	*amazonicus84*		176				176
24	CYCLOPOIDA		*Unident.*						45415	45,415
25	CALIGIDAE		*Caligus*	*spp.*	41	8				49
26	BRANCHIURA		*Argulus*	*spp.*		4		8		12
27	STOMATOPODA		*Squilla*	*empusa*	89	176	8	4		277
28	STOMATOPODA		*Unident.*						7	7
29	MYSIDACEA	MYSIDAE	*Americamysis*	*bigelowi*			84	80815		80,899
30	MYSIDACEA	MYSIDAE	*Americamysis*	*almyria*		376	3798		22941	27,115
31	MYSIDACEA	MYSIDAE	*Bowmaniella*	*floridana*	827	180	20	4		1,031
32	MYSIDACEA	MYSIDAE	*Bowmaniella*	*dissimilis*					4	4
33	MYSIDACEA	MYSIDAE	*Metamysiopsis*	*munda*	4					4
34	MYSIDACEA	MYSIDAE	*Heteromysis*	*formosa*	96					96
35	MYSIDACEA	MYSIDAE	*Mysidopsis*	*furca*			32			32
36	AMPHIPODA,	AMPELISCIDAE	*Ampelisca*	*abdita*					4	4
37	AMPHIPODA,	AMPHILOCHIDAE	*Gitanopsis*	*laguna*					199	199
38	AMPHIPODA,	AORIDAE	*Grandidierella*	*bonnieroides*			128		324	452
39	AMPHIPODA,	COROPHIIDAE	*Apocorophium*	*lacustre*					1009	1,009
40	AMPHIPODA,	COROPHIIDAE	*Monocorophium*	*sp.*					3	3
41	AMPHIPODA,	COROPHIIDAE	*Photis*	*sp.*			192		2	194
42	AMPHIPODA,	GAMMARIDAE	*Gammarus*	*mucronatus*	88	352	247	8		695
43	AMPHIPODA,	GAMMARIDAE	*Gammarus*	*tigrinus*					192	192
44	AMPHIPODA,	GAMMARIDAE	*Gammarus*	*sp.*					736	736
45	AMPHIPODA,	ISCHYROCERIDAE	*Cerapus*	*benthophilus*			2912	6038	448	9,398
46	AMPHIPODA,	ISCHYROCERIDAE	*Cerapus*	*tublularis*	24857	33848	5473			64,178
47	AMPHIPODA,	ISCHYROCERIDAE	*Erichthonius*	*brasiliensis*					1	1
48	AMPHIPODA,	OEDICEROTIDAE	*Americhelidium*	*americanum*					1	1
49	AMPHIPODA,	CAPRELLIDAE	*Caprella*	*andreae*	83					83
50	AMPHIPODA,	CAPRELLIDAE	*Caprella*	*sp.*			48		19	67

Appendix H.
Ranking of Wet, Median and Dry Rainfall Conditions for the St. Lucie Watershed

Table H.1. Ranking of wet, median (normal), and dry rainfall conditions for the St. Lucie Watershed based on rainfall data obtained from the South Florida Water Management Model

Percent of Time Annual Rainfall Was Equaled or Exceeded	Total Annual Rainfall (Ranked Highest to Lowest)	Year	Comments
2.4%	76.65	1994	~ 1-in-10 wet year = 64.25 inches
4.9%	66.60	1982	
7.3%	64.59	2005	
9.8%	64.25	1966	
12.2%	63.81	1969	
14.6%	63.10	1995	
17.1%	61.88	1992	
19.5%	60.11	1983	
22.0%	57.59	1993	
24.4%	57.22	1998	
26.8%	56.83	1970	
29.3%	56.63	1991	
31.7%	55.92	1968	
34.1%	53.86	1979	
36.6%	53.78	1999	
39.0%	53.68	1979	
41.5%	52.35	1973	
43.9%	52.23	1978	Average = 52.26 inches
46.3%	51.86	1997	
48.8%	51.28	1986	
51.2%	50.50	1996	Median = 50.50 inches
53.7%	50.33	1971	
56.1%	50.31	2001	
58.5%	49.46	1984	
61.0%	49.33	2003	
63.4%	49.26	1965	
65.9%	49.09	1967	
68.3%	48.32	1972	
70.7%	47.77	1976	
73.2%	47.76	1977	
75.6%	47.74	1985	
78.0%	47.58	1974	
80.5%	45.90	1975	
82.9%	45.17	1987	
85.4%	44.61	2002	
87.8%	44.29	1990	
90.2%	43.28	1988	~ 1-in-10 dry year = 43.28 inches
92.7%	42.21	1989	
95.1%	39.35	2000	
97.6%	39.00	1980	
100.0%	37.24	1981	