SOUTH FLORIDA WATER MANAGEMENT DISTRICT

TECHNICAL DOCUMENT TO SUPPORT REEVALUATION OF THE MINIMUM FLOW CRITERIA FOR THE CALOOSAHATCHEE RIVER ESTUARY

FINAL REPORT
JANUARY 30, 2018

South Florida Water Management District

West Palm Beach, FL

EXECUTIVE SUMMARY

The purpose of this technical document is to document and validate the data, methods, and assumptions used by the South Florida Water Management District (SFWMD) to reevaluate the minimum flows and minimum water levels (MFL) for the Caloosahatchee River (Subsection 40E-8.221(2), Florida Administrative Code (F.A.C.)). The Caloosahatchee River is in Lee County, Florida. It is defined as the surface waters that flow through the S-79 structure, combined with tributary contributions below the S-79 structure that collectively flow southwest to San Carlos Bay (Subsection 40E-8.021(2), F.A.C.). When referring to the river and estuary generally, the acronym CRE is utilized. The surface area of the CRE is 67.6 square kilometers with an average depth of 2.7 meters (Buzzelli et al. 2013a). The Franklin Lock and Dam (S-79 structure) located near Olga, Florida, serves as the upstream boundary for the CRE. The area between the S-79 structure and Shell Point can contain fresh water, marine water, or brackish water (a combination of fresh and marine waters).

An MFL is the “limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area.” (Section 373.042(1), Florida Statutes (F.S.)). SFWMD defines significant harm as the “temporary loss of water resource functions which result from a change in surface or groundwater hydrology, that takes more than two years to recover, but which is considered less severe than serious harm.” (Subsection 40E-8.021(31), F.A.C.). The water resource functions protected under Chapter 373, F.S., include flood control, water quality protections, water supply and storage, fish and wildlife protection, navigation, and recreation. In setting an MFL, water management districts must consider any changes and structural alterations that have occurred. If the MFL waterbody does not, or is not expected to, meet the proposed MFL criteria during the planning horizon, the water management district must develop a recovery or prevention strategy.

The CRE MFL Watershed is a highly altered system due to anthropogenic impacts associated with agricultural and urban development since the 1880s. Water control structures S-77, S-78, and S-79 have been constructed. Multiple dredging events have also occurred within the watershed. The C-43 Canal is part of the Central and Southern Florida Flood Control Project (C&SF Project) and the Okeechobee Waterway. The C&SF Project is a multi-objective project that provides for flood control, water supply, navigation, recreation, and the ecological functions of Lake Okeechobee and the downstream portions of the canal. These watershed changes have created a unique set of constraints that must be carefully balanced to meet the multiple objectives that exists today.

These alterations significantly reduced the storage capacity within the watershed and changed the timing, distribution, and delivery of fresh water to the CRE. Currently, there is high seasonal variation in freshwater inflow. In the wet season, high freshwater inflow results in low salinity conditions throughout most of the CRE. During the dry season, inflows can be very low to non-existent, resulting in saline intrusion that can extend upstream to the S-79 structure.

This MFL reevaluation addresses many of the major criticisms identified in the November 2000 independent scientific peer review (Edwards et al. 2000). Some of the improvements include application of a hydrodynamic salinity model and a numerical population model for *Vallisneria americana* (also known as *Vallisneria* or tape grass) and the incorporation of flow data from tributaries into a watershed model to address the contribution of flows to the CRE from the

downstream Tidal Caloosahatchee Subwatershed. Multiple ecological indicators were evaluated to document the effects of flows on biota throughout the CRE.

The science supporting this reevaluation involved a comprehensive assessment of the effects of dry season (November–April) freshwater inflows on the CRE. The dry season was chosen because these are times when the existing MFL criteria are likely to be exceeded or violated. The science effort was composed of 11 component studies focused on hydrodynamics, water column and benthic habitats, and faunal indicators. The component studies emphasized the relationships between the indicators and inflows through the S-79 structure in the dry season. The recommended MFL criteria were developed using a resource-based approach to determine minimum freshwater inflow requirements. in coastal systems throughout South Florida (Hunt et al. 2005, SFWMD 2000, 2002a, b, 2003, 2006b). The approach combines the Valued Ecosystem Component (VEC) Approach (USEPA 1988) and the habitat overlap concept of Browder and Moore (1981). The approach studied the minimum flow requirements of the various indicator species in terms of magnitude, duration, and return frequency.

The recommended MFL criteria are as follows:

- A mean monthly flow of 400 cubic feet per second (cfs) measured at the S-79 structure.
- An MFL exceedance occurs during a 365-day period when the 30-day moving average flow at S-79 declines below 400 cfs and the daily average salinity at the Ft. Myers station has exceeded 10 for more than 55 consecutive days.
- An MFL violation occurs when an exceedance occurs more than once in a five-year period.

In addition to the component studies, the recommended MFL criteria and existing recovery strategy were evaluated using a suite of hydrologic and ecological models simulating (1) long-term freshwater inflow to the CRE associated with varying management options; (2) the resulting salinity in the CRE; and (3) ecological response of indicator species that are sensitive to low freshwater inflows. Five models were utilized, three models to simulate freshwater inflows to the CRE (two for S-79 flows and one for Tidal Caloosahatchee Subwatershed flows), a three-dimensional hydrodynamic salinity model, and a *Vallisneria* model.

Integrated models were used to evaluate the existing MFL recovery strategy. Currently, during dry periods, flows to the CRE do not meet the recommended revised MFL criteria. This is consistent with the technical analysis that was completed for the 2003 MFL reevaluation which stated that the MFL criteria will be exceeded on a regular and continuing basis until additional storage is provided in the basin to supply the additional water needed (SFWMD 2003). Therefore, the approved recovery strategy will remain in place. As outlined in Appendix C of the *2017 Lower West Coast Regional Water Supply Plan Update Appendices* (SFWMD 2017), the recovery strategy is the (1) construction and operation of the Caloosahatchee River (C-43) West Basin Storage Reservoir, and (2) adoption of a water reservation to reserve from consumptive use all water within and released from the reservoir for the protection of fish and wildlife in the CRE. Construction of the reservoir should be completed by 2022. An operational testing and monitoring phase (1 to 2 years) will occur before the reservoir is put into full operation. The water reservation was adopted in May 2014.

Results of this reevaluation indicate that, once ongoing construction of the reservoir is complete and it becomes operational, excess flows during the wet season will be captured and stored in the reservoir, and the release of this stored water to the CRE during the dry season will provide the additional flows needed to meet the recommended MFL criteria and prevent significant harm.

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ACRONYMS, ABBREVIATIONS, AND UNITS OF MEASUREMENT

∞	significance
°C	degrees Celsius
$°C^{-1}$	per degrees Celsius
# m^{-2}	number per square meter
# m^{-3}	number per cubic meter
#/m^2	number per square meter
#/m^3	number per cubic meter
$\%I_0$	percentage of surface irradiance at the bottom (model parameter)
η	variable water level (model parameter)
µg L^{-1}	micrograms per liter
µm	micrometer
µmoles m^{-2} d^{-1}	micromoles per square meter per day
µmoles m^{-2} s^{-1}	micromoles per square meter per second
a_{CHL}	attenuation factor for chlorophyll *a* (model parameter)
a_{color}	constant for salinity-color relationship (model parameter)
a_{NTU}	attenuation factor for turbidity (model parameter)
A_{saw}	area of sawfish habitat
ac	acre
ac-ft	acre-foot
AET	actual evapotranspiration
AFSIRS	Agricultural Field Scale Irrigation Requirements Simulation
AFSIRS/WATBAL	Agricultural Field Scale Irrigation Requirements Simulation/Water Balance
AGWETP	groundwater evaporation potential (model parameter)
AM2	amplitude at the water level tide (M_2) determined for the Ft. Myers monitoring station (model parameter)

ANCOVA	analysis of covariance
ANOVA	analysis of variance
APRS	Adaptive Protocol Release Study
ASR	aquifer storage and recovery
Avg, avg	average
B	bottom
b_{color}	constant for salinity-color relationship (model parameter)
BMP	best management practice
BR31	Bridge 31
C_{init}	initial *Vallisneria* biomass values (model parameter)
C_{max}	maximum *Vallisneria* biomass (model parameter)
C_{shoot}	changes in aboveground biomass of *Vallisneria* (model parameter)
C&SF Project	Central and Southern Florida Flood Control Project
C-43 Reservoir	Caloosahatchee River (C-43) West Basin Storage Reservoir
CAN_CONDUCTANCE	tertiary canal bed conductance (model parameter)
CANPMPPARM	land use tertiary canal drainage pump rate (model parameter)
CDOM	colored dissolved organic matter
CEPP	Central Everglades Planning Project
CEPSC	interception storage capacity (model parameter)
CERP	Comprehensive Everglades Restoration Plan
cfs	cubic foot per second
CH3D	Curvilinear Hydrodynamic Three Dimensional Model
CHL	chlorophyll *a* concentration
CHL_{max}	chlorophyll *a* maximum concentration
cm	centimeter
Co-Pt	cobalt platinum (unit of measurement)
COA	center of abundance
Conservancy	Conservancy of Southwest Florida

CPUE	catch per unit effort
CRE	Caloosahatchee River Estuary
CRE MFL	Caloosahatchee River Estuary Minimum Flows and Minimum Water Levels
d	day
d^{-1}	per day
DBHYDRO	South Florida Water Management District's corporate environmental database
District	South Florida Water Management District
DO	dissolved oxygen
EAA	Everglades Agricultural Area
ECB	Existing Condition Baseline
ECBO	Existing Condition Baseline without reservoir
ECBW	Existing Condition Baseline with reservoir
ECBW300	Existing Condition Baseline with reservoir, targeting 300 cfs at S-79
ECBW400	Existing Condition Baseline with reservoir, targeting 400 cfs at S-79
EFDC	Environmental Fluid Dynamic Code
ENP	Everglades National Park
ERTP	Everglades Restoration Transition Plan
ET	evapotranspiration
F.A.C.	Florida Administrative Code
F.S.	Florida Statutes
FAS	Floridan aquifer system
FCB	Future Condition Baseline
FCBO	Future Condition Baseline without reservoir
FCBW	Future Condition Baseline with reservoir
FCBW300	Future Condition Baseline with reservoir, targeting 300 cfs at S-79
FCBW400	Future Condition Baseline with reservoir, targeting 400 cfs at S-79

FDEP	Florida Department of Environmental Protection
FE	federally-designated endangered
FEB	flow equalization basin
FLUCCS	Florida Land Use, Cover, and Forms Classification System
fS_{gross}	gross production of *Vallisneria* (model parameter)
fS_{loss}	mortality of *Vallisneria* (model parameter)
FSAID	Florida Statewide Agricultural Irrigation Demand Geodatabase
ft	foot
FT	federally-designated threatened
ft/day	feet per day
fT_{shoot}	photosynthesis-irradiance relationship (model parameter)
FWC	Florida Fish and Wildlife Conservation Commission
G	gross production of *Vallisneria* (model parameter)
G_{shoot}	gross production of *Vallisneria* (model parameter)
$gC\ m^{-2}$	grams shoots per square meter
$gC\ m^{-2}d^{-1}$	grams shoots per square meter per day
gdw	grams dry weight
$gdw\ m^{-2}$	grams dry weight per square meter
GIS	geographic information system
GPS	global positioning system
GUI	graphical user interface
Gz	grazing on *Vallisneria* (model parameter)
Gz_{shoot}	herbivorous grazing on *Vallisneria* (model parameter)
h	depth (model parameter)
hr	hour
HSPF	Hydrologic Simulation Program - Fortran
I_0	irradiance at the water surface (model parameter)
I_{amp}	amplitude of surface irradiance (model parameter)

I_k	half-saturation irradiance value (model parameter)
I_z	irradiance at the sediment (model parameter)
IAS	intermediate surficial aquifer
IDR	inter-decile range
in/hr	inches per hour
INFEXP	parameter in infiltration function (model parameter)
INFILD	parameter in infiltration function (model parameter)
INFILT	infiltration rate (model parameter)
INTFW	interflow coefficient (model parameter)
IRC	interflow recession constant (model parameter)
IWATER	Hydrologic Simulation Program – Fortran Module for Impervious Areas
k_{chl}	attenuation coefficient for chlorophyll
k_{color}	attenuation coefficient for color (model parameter)
K_t, k_t	total light attenuation coefficient
k_{turb}	attenuation coefficient for turbidity
k_w	total attenuation coefficient for pure water (model parameter)
kg	kilogram
kGz	basal grazing rate for *Vallisneria* (model parameter)
km	kilometer
kM	basal rate of mortality for *Vallisneria* (model parameter)
km^2	square kilometer
kN	*Vallisneria* source of new shoots (model parameter)
kR	basal rate of respiration for *Vallisneria* (model parameter)
kS_{loss}	salinity-specific loss rate (model parameter)
KT1, kT1	*Vallisneria* temperature constant for photosynthesis (model parameter)
KT2, kT2	*Vallisneria* temperature constant for photosynthesis (model parameter)

KtB	rate constant for temperature effect (model parameter)
L	length
lb	pound
lbs/trap	pounds per trap
lbs/trap/inch	pounds per trap per inch
LECSA	Lower East Coast Service Area
LiDAR	Light Detection and Radar
LNWR	Arthur R. Marshall Loxahatchee National Wildlife Refuge
LORS2008	Lake Okeechobee Regulation Schedule of 2008
LOSA	Lake Okeechobee Service Area
LOWSM	Lake Okeechobee Water Shortage Management
LSZ	low salinity zone
LWC	Lower West Coast
LZETP	lower zone evaporation potential (model parameter)
LZS	lower zone storage
LZSN	lower zone nominal storage (model parameter)
m	meter
M, M_{shoot}	shoot mortality of *Vallisneria* (model parameter)
m^{-1}	per meter
m^2	square meter
$m^2\ gdw^{-1}$	square meter per grams dry weight
m^{-2}	per square meter
M2	tidal water level
m^3	cubic meter
m^3mg^{-1}	cubic meters per milligram
m^3s^{-1}	cubic meters per second
M_{shoot}	salinity-based mortality of *Vallisneria* (model parameter)
MDL	maximum developable limit

MDS	multi-dimensional scaling
MFL	minimum flows and minimum water levels
MFL Technical Document	July 2017 draft of this document
mg L^{-1}	milligrams per liter
MGD	million gallons per day
MGM	million gallons per month
mi	mile
MIKE SHE	an integrated hydrological modeling system for building and simulating surface water flow and groundwater flow
mm/yr	millimeters per year
MSL	mean sea level (model parameter)
MWD	Modified Water Deliveries to Everglades National Park Project
n	sample size
N_{shoot}	*Vallisneria* new shoots (model parameter)
NAVD88	North American Vertical Datum of 1988
NEEPP	Northern Everglades and Estuaries Protection Program
NEXRAD	Next Generation Radar
NGVD29	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration
NPDF	normal probability density function
NSE	Nash-Sutcliffe Efficiency
NSUR	Manning's n for land surface (model parameter)
NTU	nephelometric turbidity unit; turbidity (model parameter)
NTU^{-1}	nephelometric turbidity unit
oysters/m^2	oysters per square meter
PET	potential evapotranspiration
PET Coefficient	evaporation scale factor (model parameter)
p	probability

P_m	maximum rate of photosynthesis (model parameter)
P_{photo}	photoperiod (model parameter)
PhM2	phase angle of the water level tide (M2) determined for the Ft. Myers monitoring station (model parameter)
PIR	project implementation report
PMP_LC	tertiary canal depth for stopping pump (model parameter)
PMP_UC	tertiary canal depth for triggering pump (model parameter)
POR	period of record
Proj	project
PWATER	Hydrologic Simulation Program – Fortran Module for Pervious Areas
Q	average monthly inflow
Q_{calc}	inflow rate associated with a salinity of 10 at the Ft. Myers monitoring station
Q_I	indictor inflow
Q_{inflow}	inflow rate
Q_{S79}	inflow at S-79
Q_{TB}	inflow at the Tidal Basin
r	root mean square correlation coefficient
R	respiration rate of *Vallisneria* (model parameter)
r^2	degree of fit
R^2	coefficient of determination
R_{shoot}	respiration for *Vallisneria* (model parameter)
RECOVER	Restoration Coordination and Verification Program
rkm	distance of a station from Shell Point
rkm_U	density-weighted center of abundance for each sampling event
RMS	root mean square
RMSE	root mean square error
S	salinity or surface

S_{10}	salinity of 10
S_{12}	position of salinity of 12
S_{18}	position of salinity of 18
S_{27}	position of salinity of 27
S_{30}	position of salinity of 30
S_{FtM}	average monthly salinity at the Ft. Myers monitoring station
S_{site1}	salinity at Submerged Aquatic Vegetation Monitoring Site 1
S_{U}	density-weighted salinity
S_{val1}	daily salinity at SAV monitoring Site 1 (model parameter)
SAS	surficial aquifer system
SAV	submersed aquatic vegetation
SCCF	Sanibel-Captiva Conservation Foundation
Science Summary	July 2017 draft of Appendix A of this document
SD	standard deviation
SERFIS	Surveying Estuarine Response to Freshwater Inflows
SFWMD	South Florida Water Management District
SFWMM	South Florida Water Management Model
SLR	sea level rise
SSC	species of special concern
SSURGO	Soil Survey Geographic Database
ST	state-designated threatened
STA	stormwater treatment area
T	temperature
T_{opt}	optimum temperature (model parameter)
T_{w}	water temperature (model parameter)
Tfx	temperature effect (model parameter)
Tfx_{shoot}	*Vallisneria* photosynthesis termperature effect (model parameter)

TM2	period of the water level tide (M2) determined for the Ft. Myers monitoring station (model parameter)
TMDL	total maximum daily load
TSS	total suspended solids
UKISS Model	Upper Kissimmee Model
USACE	United States Army Corps of Engineers
USFWS	United States Fish and Wildlife Services
USGS	United States Geological Survey
UZSN	upper zone nominal storage (model parameter)
V_{saw}	habitat volume for sawfish
V_{shoot}	*Vallisneria* shoot biomass
VEC	valued ecosystem component
W	Shapiro-Wilk's test
WaSh Model	Watershed Model
WATBAL	Water Balance Module for the Agricultural Field Scale Irrigation Requirements Simulation
WCA	water conservation area
WERP	Western Everglades Restoration Project
WMA	wildlife management area
WSE	Water Supply and Environmental (Schedule)
WY	Water Year; the time from May 1 to April 30 of the subsequent year, named for the year in which it ends
z	sediment elevation (model parameter

CHAPTER 1: INTRODUCTION

BACKGROUND AND PURPOSE

The Florida Water Resources Act, Chapter 373, Florida Statutes (F.S.), provides the South Florida Water Management District (SFWMD or District) with a variety of tools to conserve, protect, manage, and control water resources across a wide range of water demands and hydrologic variability. These tools provide for the allocation of water to reasonable beneficial uses, water storage, and flood control; the preservation of natural resources, fish, and wildlife; and recreational opportunities; and ensure the navigability of rivers and harbors and the health, safety, and general welfare of the people of South Florida.

Water resource protection criteria for regulation of consumptive uses are contained in Chapter 40E-2, Florida Administrative Code (F.A.C.), and the *Applicant's Handbook for Water Use Permit Applications within the South Florida Water Management District* (SFWMD 2015). In addition to these criteria, SFWMD uses three regulatory mechanisms that are adopted by rule to protect water supplies for natural systems: minimum flows and minimum water levels (MFLs), water reservations, and restricted allocation areas.

The purpose of this reevaluation of the Caloosahatchee River MFL was to reexamine the technical and scientific basis of the existing MFL criteria based on new information and peer review. Updated modeling tools and statistical approaches were utilized as well as existing and new data obtained since the initial MFL rule adoption in 2001. The responses of multiple ecological indicators to low freshwater inflows in the dry season were assessed with a resource-based approach. The appropriate MFL criteria needed to prevent significant harm to the water resource functions of the Caloosahatchee River Estuary (CRE) were determined based on the results of this reevaluation.

This chapter generally discusses the basis for MFL development and adoption, role of MFLs in water resource protection, recovery and prevention strategies, and water resource functions. It then summarizes the initial Caloosahatchee River MFL adopted in 2001 (SFWMD 2000) and associated peer review (Edwards et al. 2000), and the MFL reevaluation completed in 2003 (SFWMD 2003). A summary is provided of the direction given by the SFWMD Governing Board in 2010 to obtain the best available information for this MFL reevaluation.

BASIS FOR MFL DEVELOPMENT AND ADOPTION

Section 373.042, F.S., authorizes Florida water management districts to establish MFLs for priority surface waters and aquifers within their jurisdictions. The goal of an MFL is to prevent significant harm from occurring to the waterbody from consumptive use withdrawals. The MFL criteria threshold is not considered a sustainable condition or indicative of a healthy natural system. Significant harm is defined as the "temporary loss of water resource functions, which results from a change in surface or ground water hydrology, that takes more than two years to recover, but which is considered less severe than serious harm" (Subsection 40E-8.021(31), F.A.C.). MFL rules contain specific criteria based on existing best available information. MFL criteria are periodically reevaluated and revised as needed based on new information and changing water resource conditions.

MFL Role in Water Resource Protection

MFLs are not "stand alone" resource protection tools. MFLs must be considered in conjunction with the other resource protection responsibilities of the water management district. These include regulatory components, operating the C&SF Project, and implementing water supply planning. The Florida Legislature identified the various levels of protection that the consumptive use permitting program, MFLs, water reservation, and water shortage programs provide to the water resources. The consumptive use permitting program is implemented to prevent harm to the water resource (Section 373.219, F.S.). MFLs are meant to prevent significant harm to the water resources or the ecology of the area due to further withdrawals (Sections 373.042 and 373.0421, F.S.). The water shortage program is designed to prevent serious harm to the water resource (Sections 373.175 and 373.246, F.S.). Additionally, water management districts may reserve water from use by consumptive use permit applicants as is required for the protection of fish and wildlife or public health and safety (Section 373.223(4), F.S.). A conceptual model identifying the relationships between these water resource protection requirements is shown in **Figure 1**.

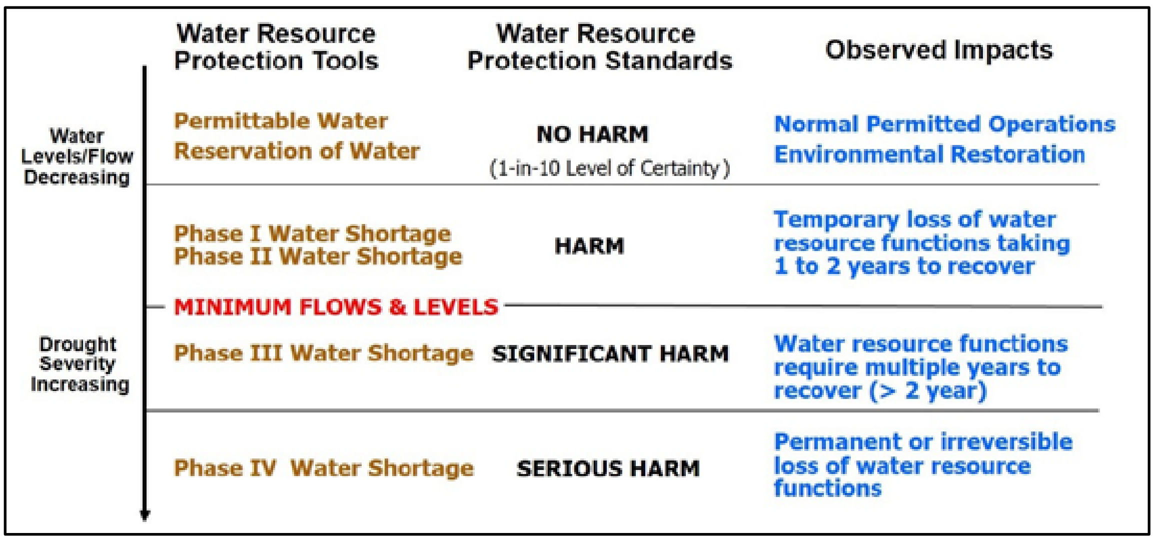


Figure 1. Conceptual relationship among the harm, significant harm, and serious harm water resource protection standards (Rules 40E-8.021(9), (31), and (30), F.A.C.). Water shortage decarations require existing legal users to reduce their permitted allocations by 15, 30, 45, and 60 percent from Phase 1 to Phase IV.

SFWMD manages the water resources and ensures their sustainability around a common level-of-certainty concept (1-in-10-year drought condition). Under this concept, both natural systems and permitted uses are considered to operate without withdrawal-induced harm, under hydrologic conditions up to and including a 1-in-10-year drought. When hydrologic conditions more severe than a 1-in-10-year drought occur and harm to natural systems occurs or is imminent, temporary water shortage cutbacks are imposed on the consumptive use withdrawals that are impacting the hydrology of natural systems until drought conditions subside. **Figure 1** shows the magnitude of water shortage cutbacks likely to be imposed commensurate with the severity of the drought, and the associated levels of harm and observed impacts to natural systems.

Harm to the natural system can also be caused by non-withdrawal-based hydrologic impacts, such as drainage, land use alterations, and operation of water management infrastructure. Often, natural systems impacted by these types of alterations experience harm at a higher frequency than a 1-in-10-year drought condition. In such cases, harm does not stem from withdrawals and cutbacks on withdrawals will not prevent harm or restore the system.

Recovery and Prevention Strategies

SFWMD implements MFLs through multi-faceted recovery and prevention strategies. Pursuant to Section 373.0421(2), F.S., a recovery strategy is implemented where an MFL waterbody is not meeting an established minimum flow or level, and the strategy is intended to achieve waterbody recovery to the established minimum flow or level as soon as practicable. A prevention strategy is implemented where an MFL waterbody is meeting an established minimum flow or level, but it is not expected to meet it in the next 20 years. Prevention strategies are intended to prevent the existing flow or water level in the waterbody from falling below the established minimum flow or level. Recovery and prevention strategies are developed as much as possible within the regional water supply planning process, and according to the 20-year water supply planning horizon.

The recovery or prevention strategy identifies those actions and projects, which, once completed, allow a waterbody to meet minimum flow or level criteria. The recovery or prevention strategy must include a phased-in approach or timetable. A number of factors influence a water management district's ability to implement proposed actions in a timely manner, including funding availability, planning, detailed design development, regulatory permitting, land acquisition, and implementation of updated permitting rules.

All recovery and prevention strategies developed by SFWMD are adopted simultaneously with adoption of the MFL rules for each waterbody. If the MFL is revised, the prevention and recovery strategy must be revisited to ensure that implementation of the strategy will enable the water resource to meet the MFL criteria. If the recovery or prevention strategy must be revised, it is to be approved simultaneously with the approval of the revised MFL (Subsection 62-40.473(5), F.A.C.). Recovery and prevention strategies for specific MFL waterbodies are included in applicable SFWMD regional water supply plans (available at www.sfwmd.gov/our-work/water-supply) and in Rule 40E-8.421, F.A.C. In 2001, SFWMD adopted an MFL for the Caloosahatchee River. The recovery strategy and its reevaluation are discussed in detail in **Chapter 10**.

Water Resource Functions

Each surface waterbody or aquifer serves an array of water resource functions that must be considered in defining significant harm when setting an MFL. Since significant harm is defined as a temporary loss of water resource functions that takes more than two years to recover, the water resource functions of the specific waterbody must be identified. **Chapter 4** provides a detailed description of the relevant water resource functions of the CRE.

Considerations and Exclusions

Once the water resource functions of a waterbody to be protected have been identified, the baseline resource conditions for assessing significant harm must be defined. Considerations for making this determination are set forth in Section 373.0421(1)(a), F.S. Water management districts are required to consider changes and structural alterations to watersheds, surface waters, and aquifers and the effects such changes or alterations have had and the constraints such changes or alterations have placed on the hydrology of an affected watershed, surface water, or aquifer. The Florida Legislature acknowledged that certain waterbodies no longer serve their historical functions and recovery of those waterbodies to historical conditions may not be economically or technically feasible, and that such a recovery effort could cause adverse environmental or hydrologic impacts. The SFWMD Governing Board may determine that setting an MFL for a waterbody based on its historical condition is inappropriate. Further discussion on considerations and exclusions for the CRE MFL are provided in **Chapter 2**.

This consideration is one of the most complex policy driven portions of MFL rule development. It potentially includes balancing of economic feasibility and impacts of removing or otherwise addressing existing changes or structural constraints currently in the system. These constraints developed over time through a series of public policy decisions that, if reversed, could have far reaching implications, such as removal of roads or bridges, reduction of public water supplies, or flood impacts. The evaluation conducted herein does not address future policy determinations by the Governing Board, but rather provides the scientific foundation for MFL development including identification of flow and salinity relationships and the water resource implications of managing the hydrology under various conditions.

CRE MFL HISTORY AND FUTURE

Development of Initial 2001 MFL Criteria

In 1999, the SFWMD Governing Board identified the Caloosahatchee River as a priority waterbody for development of an MFL. The MFL was subsequently adopted in 2001, and promulgated in Subsection 40E-8.221(2), F.A.C. Therefore, the MFL is referenced in this document as the CRE MFL.

To establish the CRE MFL, the District used a combination of the valued ecosystem component (VEC) approach (USEPA 1988), and the habitat overlap concept of Browder and Moore (1981). The VEC approach was developed by the United States Environmental Protection Agency to guide monitoring programs within the National Estuary Program. The VEC approach was modified to focus on providing critical estuarine habitat. In many instances, that habitat is biological and typified by one or more prominent species (e.g. oysters). In other cases, the habitat may be physical, such as an open water oligohaline zone. For the CRE, the VEC was biological, beds of the submerged low salinity-tolerant plant *Vallisneria americana* (tape grass). At that time, the resource identified at greatest risk in the CRE was an existing 640-acre (ac) area containing beds of *Vallisneria* located in the upper estuary between Beautiful Island and the U.S. 41 Bridge in Fort Myers (**Figure 2**), from 24 kilometer (km) to 30 km upstream of Shell Point.

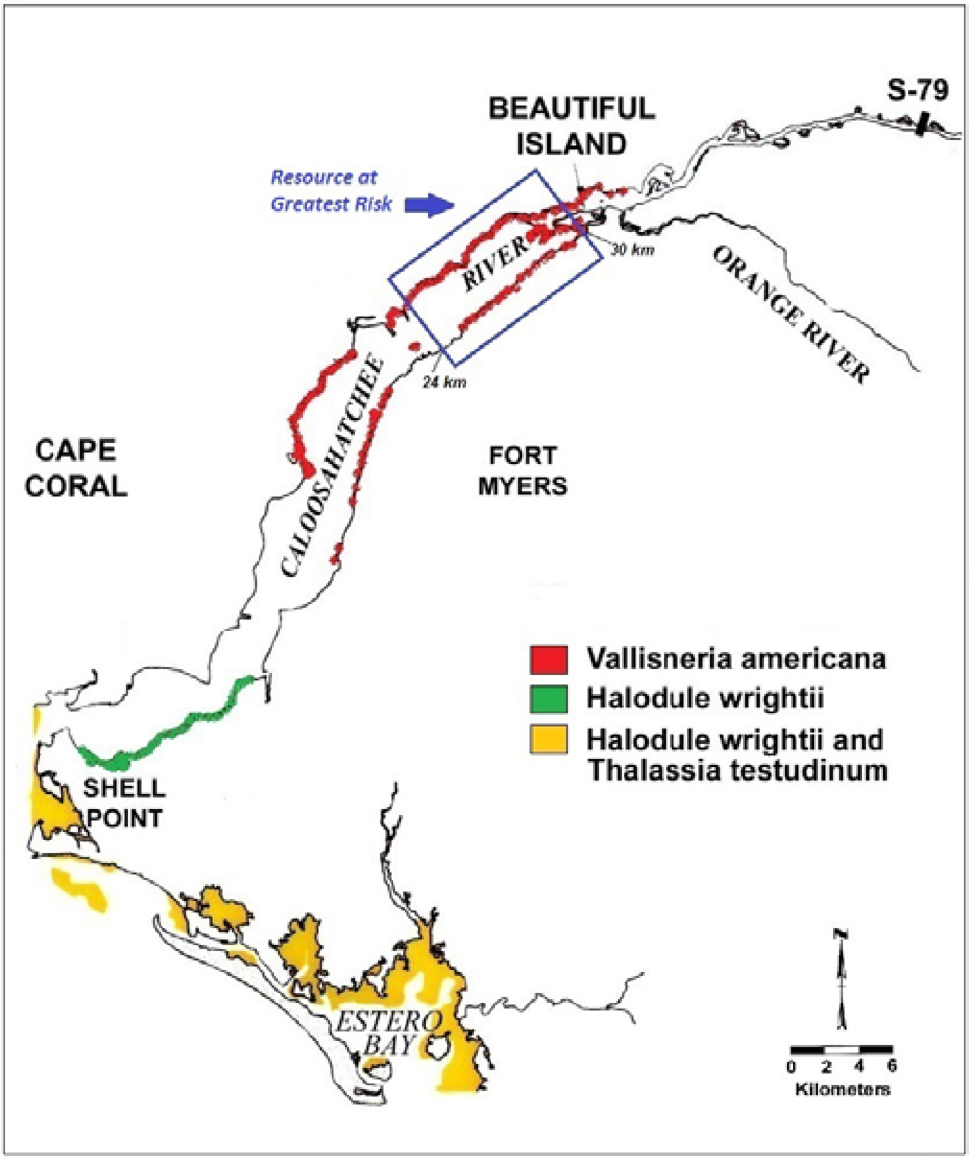


Figure 2. Resource at greatest risk in the CRE as of 2001 (illustration from Hoffacker 1994).

The MFL contained the following specific criteria in Subsection 40E-8.221(2), F.A.C., intended to protect *Vallisneria* from significant harm. A minimum mean monthly flow of 300 cubic feet per second (cfs) is necessary to maintain sufficient salinities at the S-79 structure in order to prevent an MFL exceedance. The minimum flow of 300 cfs at S-79 produced physiologically tolerable salinities (< 10) over the *Vallisneria* beds. An exceedance of the MFL occurs during a 365-day period, when either (a) a 30-day average salinity concentration exceeds 10 at the Ft. Myers salinity station (measured at 20% of the total river depth from the water surface at a location of latitude 263907.260, longitude 815209.296) or (b) a single, daily average salinity exceeds a concentration of 20 at the Ft. Myers salinity station. Exceedance of either (a) or (b) for two consecutive years is a violation of the MFL.

Conclusions of the 2000 Scientific Peer Review

As part of the original MFL development, an independent scientific peer review was conducted (see Section 373.042, F.S., and Subsection 40E-8.011(3) F.A.C). The peer review panel reviewed the proposed technical criteria and the supporting document (SFWMD 2000). The review panel generally supported the scientific approach used in establishing the MFL (Edwards et al. 2000). They also agreed the *Vallisneria* beds were an appropriate resource that needed protection and that the salinity criteria identified in the MFL were sufficient. However, the peer review panel identified specific scientific deficiencies in the MFL technical supporting document. Major criticisms of the initial effort included the following:

- Lack of a hydrodynamic/salinity model
- Lack of a numerical population model for *Vallisneria*
- No quantification of the habitat value of *Vallisneria* beds
- No documentation as to the effects of MFL flows on downstream estuarine biota

As applied here, the VEC approach assumes that MFL flows based on *Vallisneria* will not harm, and may benefit, other estuarine organisms. The scientific peer review panel concluded that this assumption was not sufficiently supported. Additional documentation was required to demonstrate that minimum flows protected organisms in the lower estuary as well as those associated with *Vallisneria* beds in the upper estuary from significant harm.

Significant harm was originally defined as occurring when loss of habitat function occurred for three consecutive years. The peer review panel concluded that this definition was not supported scientifically. Whether the frequency portion of the CRE MFL violation criteria protects against significant harm, defined as loss of habitat function that takes more than two years to recover, was not known with certainty at the time of MFL rule adoption.

In response to the 2000 peer review, the SFWMD's existing research program (SFWMD 2003; **Appendix A**) was expanded to include additional analyses of historical sampling efforts, field observations, laboratory experiments, and development of modeling tools.

2003 MFL Reevaluation

Section 373.0421(5), F.S., specifies that MFLs shall be reevaluated periodically and revised as needed. The criteria and scientific basis of the MFL were reevaluated in 2003 (SFWMD 2003) with information obtained through expansion of the SFWMD research program (SFWMD 2003; **Appendix A**), further field observations, laboratory experiments, and numerical model developments. The comments and recommendations of the 2000 peer review panel, as well as the results of addition analyses and model developments completed by SFWMD, were used.

The 2003 reevaluation specifically evaluated the ability of the 300-cfs discharge at the S-79 structure to protect the 640-ac area containing *Vallisneria*. The 2003 reevaluation is summarized in a technical supporting document, which outlines the methods and results of the additional analyses and modeling conducted, management implications, and additional investigations needed to further refine the recovery strategy (SFWMD 2003). The 2003 supporting document did not address the habitat value of *Vallisneria* beds because *Vallisneria* has been virtually absent in the CRE for approximately 14 years following the MFL adoption in 2001. However, SFWMD has implemented a study of *Vallisneria* habitat utilization in the Loxahatchee River Estuary as a surrogate study for the CRE.

The 2003 reevaluation of the MFL also concluded that the recovery strategy was required pursuant to Section 373.0421(2), F. S. The technical document stated that the MFL criteria would be exceeded on a regular and continuing basis until additional storage is provided in the basin to supply the additional water needed (SFWMD 2003). Since adoption of the MFL, the lower west coast water supply plan updates have also consistently indicated that exceedance of the MFL critera would continue until the C-43 Reservoir is constructed and operational.

2003 Conclusions

VEC Approach

The original MFL rule adopted identified salinity criteria that, if not achieved, would result in significant harm to submerged *Vallisneria* beds in the upper estuary. A major assumption of this approach was that salinity and flow conditions that protect *Vallisneria* also protect other key organisms in the estuary. It was concluded in 2003 that previous work on this subject (Chamberlain and Doering 1998) and results presented as part of the 2003 reevaluation supported the validity of this assumption.

Salinity Criteria

The existing MFL contains two salinity criteria at the Ft. Myers salinity monitoring station: (1) a 30-day average salinity of 10, and (2) a daily average salinity of 20. The 2003 results indicated that these were sound physiological and ecological thresholds for *Vallisneria* (SFWMD 2003).

Salinity and Freshwater Inflow

The 2001 MFL was based on a regression approach for estimating the relationship between salinity at the Ft. Myers station and discharge at the S-79 structure. Following the recommendation of the 2000 peer review panel (Edwards et al. 2000), a mass-balanced hydrodynamic model of the CRE was developed using the Curvilinear Hydrodynamic Three-dimensional Model (CH3D) platform (Sun et al. 2016). The regression approach explicitly considered the effects of S-79 discharge (x) on salinity (y) in the downstream estuary. However, the model only implicitly included inflows from the Tidal Caloosahatchee Subwatershed[1] downstream of S-79. Tidal Caloosahatchee Subwatershed flows are not independent variables in the regression, yet they influence salinity (y). To address this, a linear reservoir model of Tidal Caloosahatchee Subwatershed inflows was developed (SFWMD 2003) based on a recent application of the MIKE SHE model code (DHI 1998, Petersen et al. 2002). MIKE SHE is an integrated hydrological modeling system for building and simulating surface water flow and groundwater flow.

Results from the hydrodynamic model indicated that a total inflow (discharge at S-79 + Tidal Caloosahatchee Subwatershed inflow) of about 500 cfs was required to produce a salinity of 10 at the Ft. Myers station. Comparison of modeled Tidal Caloosahatchee Subwatershed flows with measured flows at S-79 indicated that, on average, when mean monthly flows at S-79 averaged 300 cfs, there was an additional 150–200 cfs flowing to the estuary from the downstream Tidal

[1] In the *Assessment of the Responses of the Caloosahatchee River Estuary to Low Freshwater Inflow in the Dry Season* document (**Appendix A**) this is referred to as the “Tidal Basin”.

Caloosahatchee Subwatershed. The 2003 reevaluation concluded that, for 300 cfs of water released at S-79 to produce a salinity of 10 at Ft. Myers, additional inflow from the downstream Tidal Caloosahatchee Subwatershed was required. The additional inflow needed was estimated with great uncertainty to be 150–200 cfs. It was recommended that before any decisions were made to modify the MFL, improved flow measurements from the Tidal Caloosahatchee Subwatershed and more robust calibration of the newly developed models were required. As part of this reevaluation, these missing flow data were collected to address this uncertainty and improve model performance.

Resource-based Evaluation of the Recovery Strategy

In response to peer review recommendations, a population level model of *Vallisneria* was developed. Shoot density at two monitoring sites was simulated. Site 1 (Bird Island) is located approximately 30 km upstream of Shell Point and Site 2 is located approximately 26 km upstream of Shell Point. Both sites were within the area to be protected for *Vallisneria* (24–30 km upstream of Shell Point) (**Figure 2**). Results from the *Vallisneria* modeling study indicated that the salinity criterion of 10 at the Ft. Myers station provides appropriate protection of the resource from significant harm.

2010 Direction for Future MFL Reevaluation

In response to public concerns about the CRE MFL, given the single-species approach (i.e. *Vallisneria*) and the limited modeling analysis that was used in its development, at the November 10, 2010, SFWMD Governing Board meeting, staff was directed to obtain the best available information to reevaluate the MFL criteria. Over the course of the next several years, a comprehensive research and monitoring program was established to do the following:

- Collect flow data from the Tidal Caloosahatchee Subwatershed (at least 5 years) to develop models (watershed, flow, and hydrodynamic) to properly simulate inflows and salinity responses.
- Update and apply a *Vallisneria* population model.
- Quantify the habitat value of *Vallisneria* beds.
- Determine effects of MFL flows on downstream estuarine organisms (e.g. oysters and benthic macrofauna).
- Analyze the return frequency for the MFL.

The Governing Board committed to funding the research that was needed to accomplish these tasks.

CHAPTER 2: ALTERATIONS AND PHYSICAL CHARACTERISTICS OF THE CRE AND ITS WATERSHED

HISTORICAL FEATURES OF THE WATERSHED

Historic Caloosahatchee River

The Caloosahatchee River was originally a natural watercourse running from its origin at Lake Flirt (near La Belle) to San Carlos Bay (**Figure 3**). The river was sinuous with many natural oxbows providing a diversity of different habitat types. It consisted of 102 river bends and oxbows covering over the 63.9 miles from Beautiful Island to Lake Okeechobee (Antonini et al. 2002). A geologic feature known as the Fort Thompson rapids, a geologic feature approximately 0.9 miles in length, separated the head of the Caloosahatchee River from its upstream contributing areas that existed at higher elevations. These upstream contributing areas consisted of interconnected marshes and three small lakes—Lake Hicpochee, Lake Bonnet, and Lake Flirt. Lake Hicpochee was the largest lake located near Lake Okeechobee. The Fort Thompson rapids were located downstream of Lake Flirt.

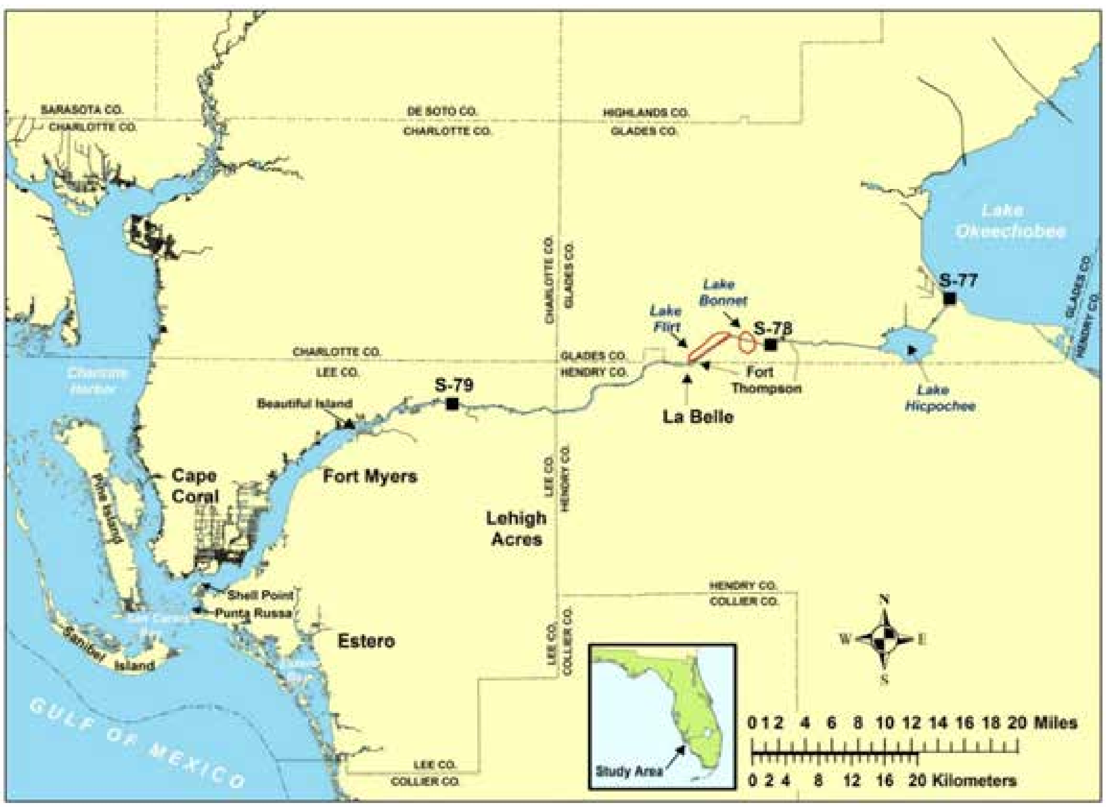


Figure 3. Caloosahatchee River showing water control structures, connection to Lake Okeechobee, and historical headwaters at Lake Flirt and Lake Bonnet.

Alterations in the Freshwater Portions of the Watershed (Upstream of S-79)

Man-made alterations to the river began as early as 1884, when private interests constructed a canal between the river headwaters and Lake Okeechobee for water control and navigation. To make the river compatible for multiple uses with different water levels, Hamilton Disston's Company created an open connection from Lake Okeechobee to the headwaters of the Caloosahatchee by 1887 (Antonini et al. 2002). Dredging alterations continued and, by 1918, three combination lock and spillway structures had been constructed at Moore Haven, Citrus Center, and Fort Thompson (USACE 1957, Section 6.B.6).

In 1930, the first federal effort at flood control in Florida occurred with the passage of the River and Harbor Act of July 3, 1930, which authorized improvement of the Caloosahatchee River and Canal (now the C-43 Canal) (U.S. Congress 1930). By 1937, the Caloosahatchee River was improved to provide a navigable channel at least 6 feet deep and 80 feet wide with locks and water control structures at Moore Haven (S-77, constructed in 1935) and Ortona (S-78, constructed in 1937). The original three locks were bypassed by the navigation channel and eventually abandoned. Under the River and Harbor Act of 1945, the C-43 Canal was improved again for navigation purposes (8 feet deep and 90 feet wide) (U.S. Congress 1945; USACE 1957, Section 6.B.6).

In 1957, the United States Army Corps of Engineers (USACE) prepared a report specifically focusing on the drainage, water control, and navigation needs of the Caloosahatchee River Basin (U.S. Congress 1948, 1954). The report recommended a plan for improvement of the C-43 Canal and structures S-77 and S-78, as well as construction of a third structure (S-79) at Olga (USACE 1957, Section I.41). The purposes and objectives for these additional improvements, as envisioned in the general design memoranda, were to provide (1) conveyance capacity for the watershed, (2) water control to prevent excessive depletion of groundwater during normal or dry periods, (3) regulatory discharge capacity for Lake Okeechobee, (4) adequate capacity so that existing navigation locks would not have to be used for flood or regulatory discharges, and (5) protection to prevent saltwater encroachment and maintenance of water supplies in the lower reaches of the C-43 Canal (USACE 1957).

Purpose of the S-79 Structure

The purpose and need for the S-79 structure are tied to the alterations made to the Caloosahatchee River (C-43 Canal) as described above. The key objectives were to (1) eliminate undesirable salinity in the lower river, (2) prevent the rapid depletion of water supplies, and (3) raise the prevailing dry weather water table levels (USACE 1958, 2D Endorsement, paragraph 9). During the wet season, S-79 was designed to be a spillway structure to pass permissible releases from Lake Okeechobee (USACE 1957, Section F.29). During the dry season, S-79 was designed to address the lack of freshwater supply for irrigation in the lower river basin, immediately upstream of S-79. Prior to construction of S-79, freshwater supply was depleted by uncontrolled downstream discharges to such an extent that the water table, as measured in wells near the river, was as much as 10 feet below ground surface (a depth of 2 or 3 feet was considered optimum) (USACE 1957, Section G.32). Currently, S-79 is operated pursuant to federal regulations and in accordance with Central and Southern Florida Flood Control Project (C&SF Project) purposes.

In 1957, a report prepared by the United States Fish and Wildlife Service (USFWS) concluded the riverine and estuarine fisheries were of relatively low quality and value due to adverse effects on the environment caused by the C-43 Canal improvements and channelization (USACE 1957; **Appendix A**). USFWS also concluded that past regulatory and flood control discharges through the river had adverse effects on the sport and commercial fisheries of the tidally-influenced areas. Finally, the USFWS determined that these poor conditions were likely to persist and may be worsened by the deepening of the channel (C-43 Canal) and the installation of the S-79 structure, and that these negative effects may be extended over a greater area, including inshore waters.

The S-79 structure was constructed in 1965. It was rededicated as the Franklin Lock in 1969. This lock and dam artificially sets the eastern limit of the Gulf of Mexico's tidal influence and consequently resulted in a truncated estuarine system that prevents saltwater from moving upstream of S-79.

The C-43 Canal was last dredged in the 1960s. The practice was abandoned when the United States Congress passed the Clean Water Act (U.S. Congress 1972) in 1972. The multiple dredging events that occurred between pre-development and current conditions shortened the river by 8.2 miles and resulted in the loss of 76 river bends (Antonini et al. 2002).

Alterations in the Watershed (Upstream of S-79)

The alterations described above allowed the CRE MFL Watershed to be developed. A network of secondary and tertiary canals now overlays the CRE MFL Watershed. This canal network provides conveyance for both drainage and irrigation to accommodate both agricultural and urban development (Flaig and Capece 1998).

The changes that occurred in the watershed upstream of S-79 have profoundly influenced the delivery of fresh water to the estuary at this water control structure. Typical of overdrained watersheds (Hopkinson and Vallino 1995), runoff is now more variable with higher wet season flows and lower dry season discharges. Large volumes of fresh water during the wet season can flush salt water from the tidally-influenced sections of the waterbody. By contrast, freshwater inflow at the S-79 structure can stop entirely during the dry season, especially during significant drought events. Salt water intrudes to the S-79 structure, sometimes reaching a salinity of 20 (Chamberlain and Doering 1998). Fluctuations of this magnitude at the head and mouth of the system cause mortality of organisms at both ends of the salinity gradient (Doering et al. 2002).

Alterations In the Estuary (Downstream of S-79)

The estuarine portion of the CRE, located downstream (west) of the S-79 structure, has also been significantly altered (Chamberlain and Doering 1998) by multiple dredging activities. Early descriptions characterize it as barely navigable, owing to extensive shoals and oyster bars (Sackett 1888). Historical oyster bars upstream of Shell Point were mined/removed and the material was used for the construction of roads. Seven automobile bridges and one railroad trestle connect the north and south shores of the estuary. To accommodate navigation, dredging also occurred within the central portions of the estuary dating back to the early 1880s (Antonini et al. 2002). A navigation channel was dredged and a causeway was built across the mouth of San Carlos Bay in the 1960s. This navigation system (Intracoastal Waterway) still exists to accommodate commercial and recreational boating activities.

A large canal network was also developed along the northern shoreline of the CRE in an area known as Cape Coral. This canal network, excavated in a grid-like pattern, began in Redfish Point in the early 1950s (Antonini et al. 2002). Fill from the canals was used to make the finish floor elevations for houses high enough to meet local land use regulations. This same type of canal waterfront housing expanded to other areas in Cape Coral and along the southern shoreline of the CRE. To provide navigational access from the canal networks to deeper water, multiple access channels were dredged within the CRE.

Alterations to the delivery of fresh water, combined with structural changes to the tidally-influenced sections of the waterbody, has had lasting ecological consequences. The Sanibel Causeway, which crosses the mouth of San Carlos Bay at Punta Rassa, may have influenced the seaward end of the system. USFWS predicted the causeway would restrict exchange with the Gulf of Mexico, retain fresh water, and lower the salinity in southern Charlotte Harbor (USFWS 1960). Reductions in salinity were predicted to adversely affect a flourishing bay scallop fishery, which collapsed after the construction of the causeway. Twenty years later, the Florida Department of Natural Resources reported a significant decline in seagrass cover in deeper areas and attributed this, in part, to an increased amount of colored fresh water (Harris et al. 1983).

CURRENT CHARACTERISTICS OF THE CRE MFL WATERSHED

The CRE MFL Watershed, C-43 Canal, and CRE are located on the lower west coast of Florida (**Figure 4**). The CRE receives surface water from Lake Okeechobee, runoff from four subwatersheds—S-4, East Caloosahatchee, West Caloosahatchee, and Tidal Caloosahatchee[2]—which are collectively defined as the CRE MFL Watershed, and a small amount of base groundwater flow from the surficial aquifer system. The watershed includes creeks, wetland tributaries, canals, and drainage ditches that provide limited storage and allow conveyance of surface water. The major tidal tributaries of the CRE are the Orange River and Telegraph Creek, which drain into the upper estuary downstream of the S-79 structure. The CRE MFL Watershed covers approximately 861,058 ac (3,485 square kilometers [km^2]), spanning parts of Lee, Glades, Hendry, Charlotte, and Collier counties. Lake Hicpochee, located west of lake Okeechobee, is the only remaining natural lake in the watershed but currently functions more like a freshwater marsh due to its shallow depth.

[2] In the *Assessment of the Responses of the Caloosahatchee River Estuary to Low Freshwater Inflow in the Dry Season* document (**Appendix A**) this is referred to as the “Tidal Basin”.

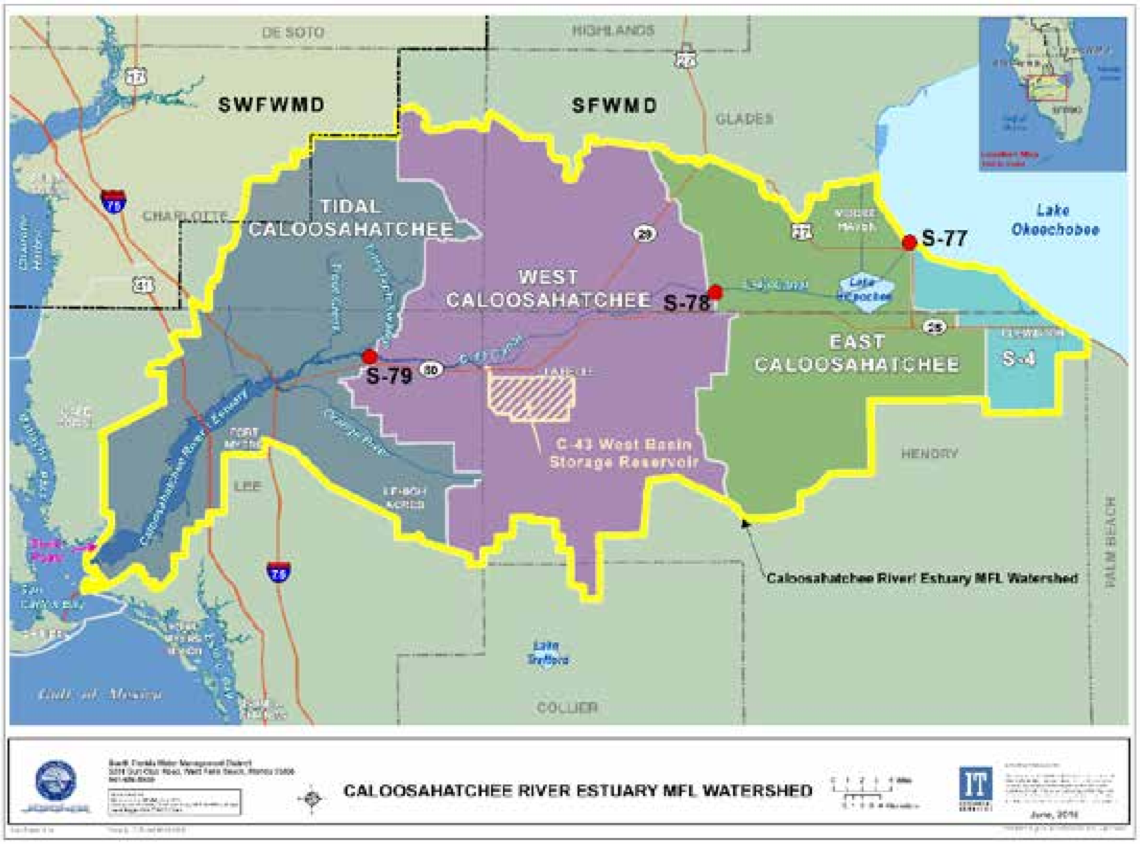


Figure 4. CRE MFL Watershed, showing the CRE, C-43 Canal, subwatersheds, water management structures, and Caloosahatchee River (C-43) West Basin Storage Reservoir site.

C-43 Canal

The C-43 Canal runs 41.6 miles (67 km) from Lake Okeechobee at Moore Haven (S-77 structure) to the Franklin Lock and Dam (S-79 structure) at Olga. This canal system serves as a conveyance feature to drain water from the three subwatersheds located upstream of the S-79 structure and also serves to convey regulatory discharges of surface water from Lake Okeechobee. The S-78 structure is located between the S-77 and S-79 structures and separates the East and West Caloosahatchee subwatersheds.

All three of the structures within the C-43 Canal are operated and maintained by USACE. Presently, the stages within the C-43 Canal are regulated as two different pools of water. Between S-77 and S-78, the C-43 Canal stage is operated to maintain an optimum headwater elevation of 11.1 feet at the S-78 structure. The stage between S-78 and S-79 is operated to maintain an optimum headwater stage of 3.0 feet at the S-79 structure.

Caloosahatchee River Estuary

Separating fresh and brackish water, the S-79 structure demarcates the head of the CRE. From the S-79 structure, the estuary extends 26 miles (42 km) downstream to Shell Point, where it empties into San Carlos Bay in the southern portion of the greater Charlotte Harbor system. The width of the estuary is irregular, ranging from 525 feet (ft or 160 meters [m]) in the upper portion to 8,200 ft (2,500 m) near its mouth. The narrow section between the S-79 structure and Beautiful

Island has a mean depth of about 20 ft (6 m), while the area downstream has an average depth of 4 ft (1.5 m) (Scarlotos 1988). The surface area of the waterbody is approximately 16,715 ac (67.6 km^2). Surface water leaving the river/estuary at Shell Point enters San Carlos Bay. Most of this water takes a southerly route, flowing to the Gulf of Mexico under the Sanibel Causeway (Goodwin 1996). When freshwater inflows are high, tidal action pushes some of this water back up into Matlacha Pass and Pine Island Sound. Additionally, some water exits to the south and flows into Estero Bay through Matanzas Pass.

The estuary has a micro tide condition inside the estuary with tidal ranges around 0.5 m or less according to long-term monitoring data by the National Oceanic and Atmospheric Administration (NOAA) and SFWMD. It has a declining trend from downstream to upstream. In the offshore area within the Gulf of Mexico at Naples, the tidal range is about 0.6 m from mean low water to mean high water with a tidal (M_2) amplitude of 0.26 m. The ranges becomes 0.51 m at the Punta Rassa station with an M_2 amplitude of 0.2 m, and then only 0.3 m at the Ft. Myers station with an M_2 amplitude of 0.11 m. The declining trend becomes less steep as it goes further upstream. At the head of the estuary, the range from mean low water to mean high water is 0.26 m.

Salinity exhibits a strong gradient in the estuary. Salt intrusion in the dry season has been an issue since the 1960s especially during dry years. One of the purposes of the S-79 structure was to prevent salt intrusion further upstream. Stratification does occur depending on freshwater flow conditions, but it is not significant during the dry season (**Figure 5**).

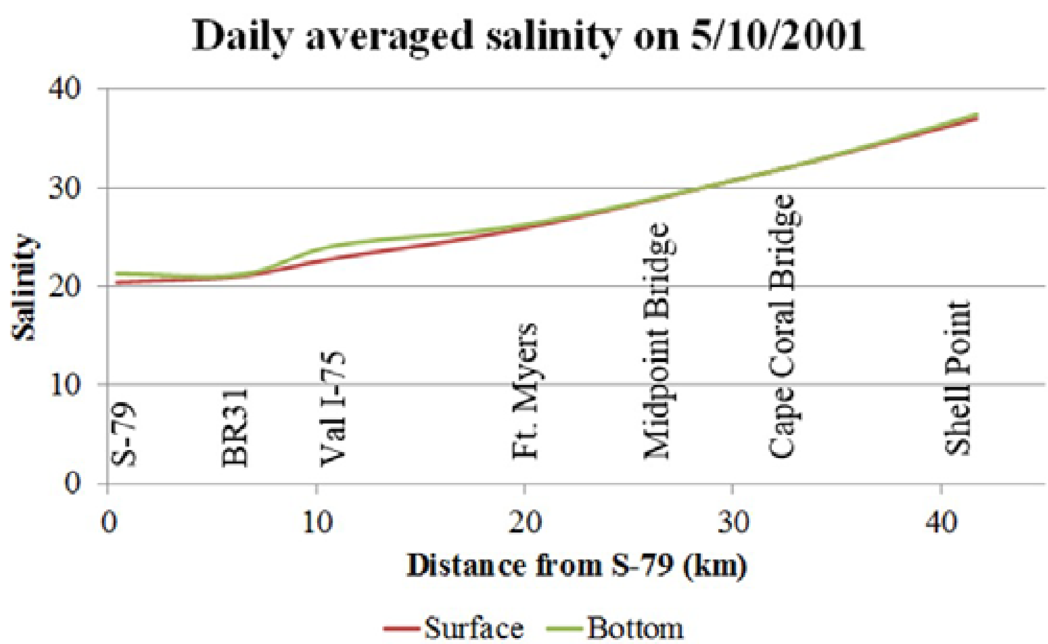


Figure 5. Daily averaged surface and bottom salinity measured at S-79, Bridge 31, Val I-75, Ft. Myers, Cape Coral, and Shell Point on May 10, 2001.

LAND USES WITHIN THE CALOOSAHATCHEE WATERSHED

Much of the early changes or alterations within the watershed were designed to allow drainage and/or navigation, which fueled the establishment of early settlements. Many of the later alterations were driven by varying or extreme climate events. The extreme flooding events ruined many early settlements and additional settlements were abandoned after multiple flood events (Antonini et al. 2002). Drought events made it difficult or impossible to navigate due to exposed shoals. Multiple drainage and dredging alterations within the watershed provided more consistent navigation and flood protection allowing various types of land uses to flourish along the waterfront and expansion into other areas.

Land uses and their associated demands highly affect the timing, delivery, and quantity of water runoff that reaches the downstream estuary. **Figure 6** shows that the current land uses within the CRE MFL Watershed are predominately agricultural in the eastern portion (S-4, East Caloosahatchee, and West Caloosahatchee subwatersheds) and urban in the western portion (Tidal Caloosahatchee Subwatershed and the eastern portion of the West Caloosahatchee Subwatershed within Lee County).

Table 1 compares the different land uses within the CRE MFL Watershed using the Level 1 Florida Land Use, Cover, and Forms Classification System (FLUCCS). The dominant land use is agriculture, covering approximately 42.1% or 362,763 ac (1,468 km^2) of the watershed. Agricultural land uses consist of cropland, pasture, citrus, nurseries, sod farms, and other specialty farms. The next largest land use within the watershed is urban and built-up land use, which is comprised of low, medium, and high density urban, commercial, industrial, mining, institutional, open land, and recreational land use categories. These land uses cover approximately 18% or 154,943 ac (627 km^2). The next two largest categories include wetlands and upland forest, covering approximately 14.6% and 14 percent of the watershed, respectively. The remaining land uses (rangeland, water, transportation/utilities, and barren lands) encompass approximately 11.3% or 97,823 ac (395.9 km^2) of the watershed.

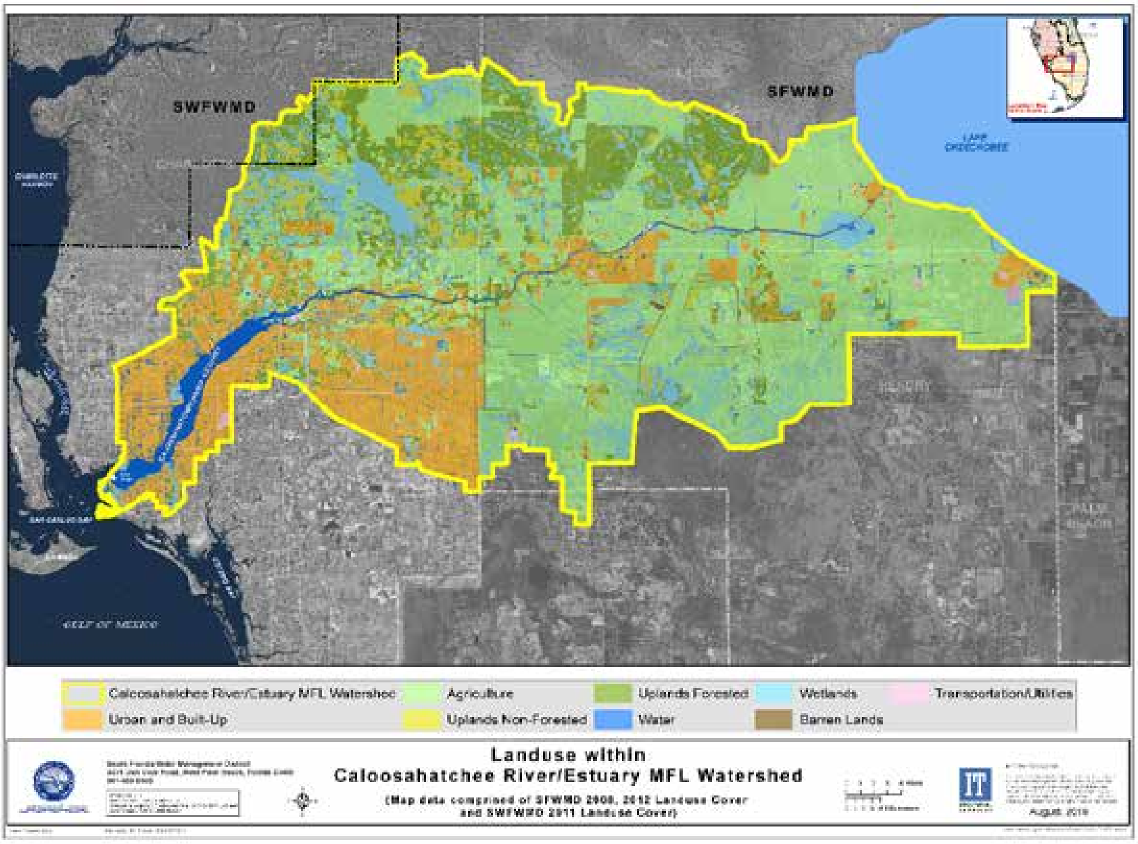


Figure 6. 2012 land uses in the CRE MFL Watershed.

Table 1. FLUCCS for the CRE MFL Watershed.[a]

FLUCCS Category (Level 1)	FLUCCS Code	Acres	Percent of Total
Agriculture	2000	362,763	42.13%
Urban and Built Up	1000	154,943	17.99%
Wetlands	6000	125,298	14.55%
Upland Forest	4000	120,230	13.96%
Rangeland	3000	56,847	6.60%
Water	5000	28,526	3.31%
Transportation/Utilities	8000	7,667	0.89%
Barren Lands	7000	4,783	0.56%
Grand Total		**861,059**	**100.00%**

a. Source: 2012 FLUCCS codes were used for SFWMD, except for an 8,269-ac area in Glades and Hendry counties near Lake Okeechobee, which used 2008 FLUCCS codes, and an 11,058-ac area in Charlotte County within the South West Florida Water Management District boundaries, which used 2011 FLUCCS codes.

SUMMARY

The CRE MFL watershed is a highly altered system that has been changed from its historic condition by anthropogenic means to accommodate agricultural and urban development since the 1880s. The construction of the S-77, S-78, and S-79 structures combined with the multiple dredging events that occurred within the former Caloosahatchee River (now the C-43 Canal) have significantly altered the historic functions that once existed. Today, the C-43 Canal is part of the C&SF Project and Okeechobee Waterway. It serves to balance multiple objectives including flood control, water supply, navigation, recreation, and the ecological functions of Lake Okeechobee and the downstream portions of the CRE.

The CRE has also undergone multiple dredging alterations to accommodate development, roadway bridges, flood control, and navigation. These actions significantly reduced the storage capacity within the watershed and changed the timing, distribution, and delivery of fresh water to the estuary. These watershed changes have created a unique set of constraints that must be carefully balanced to meet the multiple objectives that exists today.

CHAPTER 3: HYDROLOGIC CHARACTERISTICS OF THE CRE MFL WATERSHED

This chapter addresses the hydrologic characteristics of the CRE MFL Watershed. The hydrology of this watershed is strongly affected by its climate, rainfall, and seasonal weather patterns, and its low topographic relief (SFWMD 2000). The portions of the watershed located upstream of the S-79 structure are collectively referred to as the C-43 Watershed, which includes freshwater runoff from three subwatersheds that flow into the C-43 Canal. The portion of the watershed located downstream of the S-79 structure is called the Tidal Caloosahatchee Subwatershed (**Figure 4**). The runoff from this subwatershed discharges into the tidal portions of the CRE. Total flows contributing to the CRE come from three primary contributing sources: (1) flows from the C-43 Watershed (2) discharges from Lake Okeechobee and, (3) flows from the Tidal Caloosahatchee Subwatershed.

RAINFALL

Trends and Patterns

The CRE MFL Watershed has distinct dry (November–April) and wet (May–October) seasons typical of a subtropical climate. The Next Generation Radar (NEXRAD) rainfall data from 1996 to 2015 was retrieved from SFWMD's corporate environmental database, DBHYRO (www.sfwmd.gov/nexrad2), for trend and pattern analysis. The average annual rainfall over the watershed for this period is 53.05 inches (**Figure 7**) with standard deviation of 6.56 inches. The minimum annual rainfall was 42.51 inches in 1996 and maximum was 65.85 inches in 2005. Visually, the rainfall does not show an apparent trend from 1996 to 2015. A widely used non-parametric approach, the Mann-Kendall test (Mann 1945, Kendall 1975) was applied to assess this tendency. The test revealed no statistically significant temporal trend (probability [p] > 0.05). On average, 79% of annual rainfall occurred in the wet season and 21% in the dry season. This rainfall pattern causes a larger freshwater discharge to the CRE in the wet season than in the dry season (Qiu and Wan 2013).

The most severe storms of the year usually occur in the wet season and are typically associated with thundershowers, squalls, and tropical cyclones (hurricanes and tropical storms). Dry season rainfall is usually the result of large frontal systems and is broadly distributed. November and December typically have the lowest rainfall (Wan 2015).

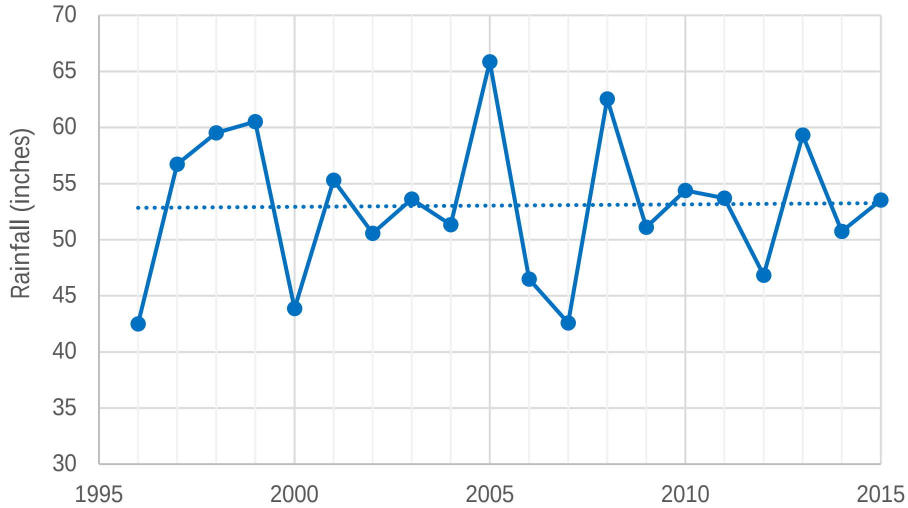


Figure 7. Annual rainfall (1996–2015) in the CRE MFL Watershed.

Average annual rainfall for the subwatersheds is shown in **Figure 8**. Spatially, the greatest annual rainfall (57.66 inches) occurred in the Tidal Caloosahatchee Subwatershed and the least in the S-4 (46.26 inches) Subwatershed. Average annual rainfall decreased from the Tidal Caloosahatchee Subwatershed toward inland subwatersheds. In other words, average annual rainfall decreases from west to east in the watershed.

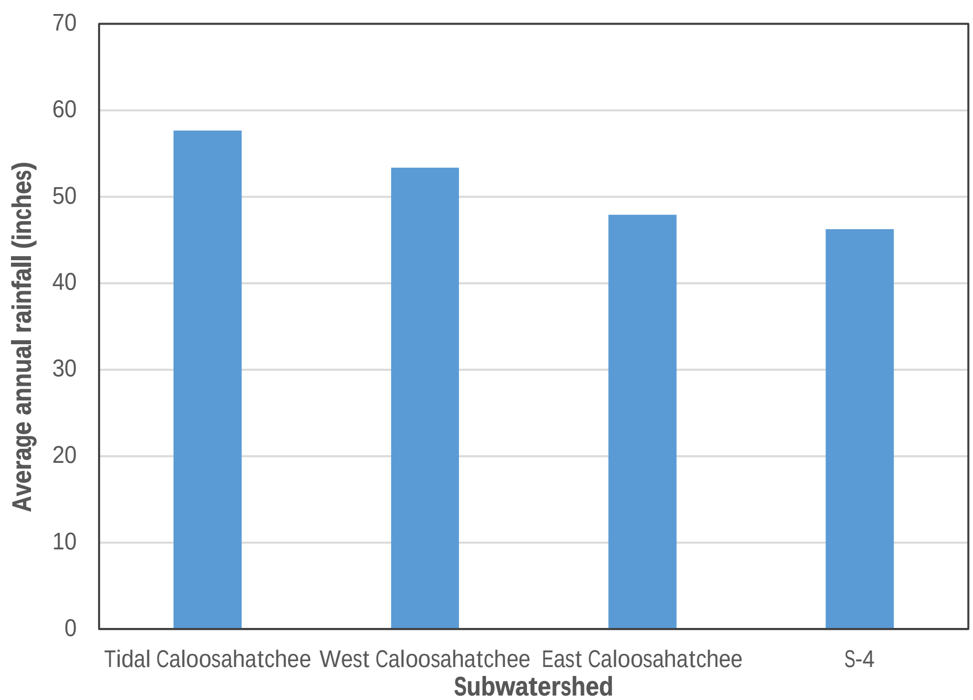


Figure 8. Average annual rainfall of subwatersheds (1996–2015) in the CRE MFL Watershed.

Drought Events

During some dry seasons, there are long periods of time in which there is little or no rainfall resulting in a regional drought. Ali and Abtew (1999) conducted a rainfall frequency analysis using a gamma distribution to estimate 1-in-10 drought levels of rainfall. This 1-in-10 drought level of rainfall was applied to develop the *2005–2006 Lower West Coast Water Supply Plan Update* (SFWMD 2006a). The statistical 1-in-10-year rainfall at the Ft. Myers station is 43.59 inches (representing the tidal area downstream of S-79) and 42.74 inches at La Belle (representing the C-43 Watershed, i.e., upstream of S-79). To apply these 1-in-10-level rainfall values to identify drought events, the annual rainfall from 1996 to 2015 was computed for the Tidal Caloosahatchee Subwatershed (downstream of S-79) and C-43 Watershed (West Caloosahatchee, East Caloosahatchee, and S-4 subwatersheds) (**Table 2**).

The annual rainfall less than 1-in-10-year level was identified with red text in **Table 2**. There were three drought years with annual rainfall less than a 1-in-10 level, which occurs when annual rainfall is at or below 42.74 inches at the La Belle weather station, in the C-43 Watershed over the past 20 years (1996, 2000, and 2007). For the Tidal Caloosahatchee Subwatershed, a 1-in10 year drought event has not occurred during the past 20 years (**Table 2**).

Table 2. Annual rainfall in inches for the Tidal Caloosahatchee Subwatershed and C-43 Watershed.[a,b]

Year	Tidal Caloosahatchee Subwatershed	C-43 Watershed
1996	46.27	40.84
1997	64.54	53.25
1998	64.67	57.25
1999	63.38	59.25
2000	48.47	41.84
2001	56.80	54.64
2002	57.49	47.48
2003	61.46	50.15
2004	59.07	47.89
2005	69.20	64.37
2006	54.70	42.83
2007	44.24	41.83
2008	64.40	61.72
2009	49.68	51.73
2010	60.02	51.89
2011	58.36	51.63
2012	52.19	44.44
2013	64.41	57.06
2014	50.62	50.81
2015	63.30	49.20

a. Source: NEXRAD rainfall data from 1996 to 2015 was retrieved from SFWMD's corporate environmental database, DBHYRO (www.sfwmd.gov/nexrad2).
b. The numbers in red indicate that a drought occurred.

GROUNDWATER AND AQUIFER SYSTEMS

The Lower West Coast (LWC) Planning Area is underlain by three primary aquifer systems: surficial aquifer system (SAS), intermediate aquifer system (IAS), and Floridan aquifer system (FAS). The SAS consists of the unconfined water table aquifer and the Lower Tamiami aquifer, separated in most places by the Tamiami confining unit. The units of the SAS primarily interact with surface water within the project area. The Sandstone and Mid-Hawthorn aquifers comprise the IAS. The IAS units interact much less with surface water, but are recharged vertically from the SAS and the FAS. The FAS underlies the IAS and is not a subject of this discussion, since it is not hydraulically connected to surface water in the LWC Planning Area. **Figure 9** shows the generalized geology and hydrogeology in the CRE MFL Watershed.

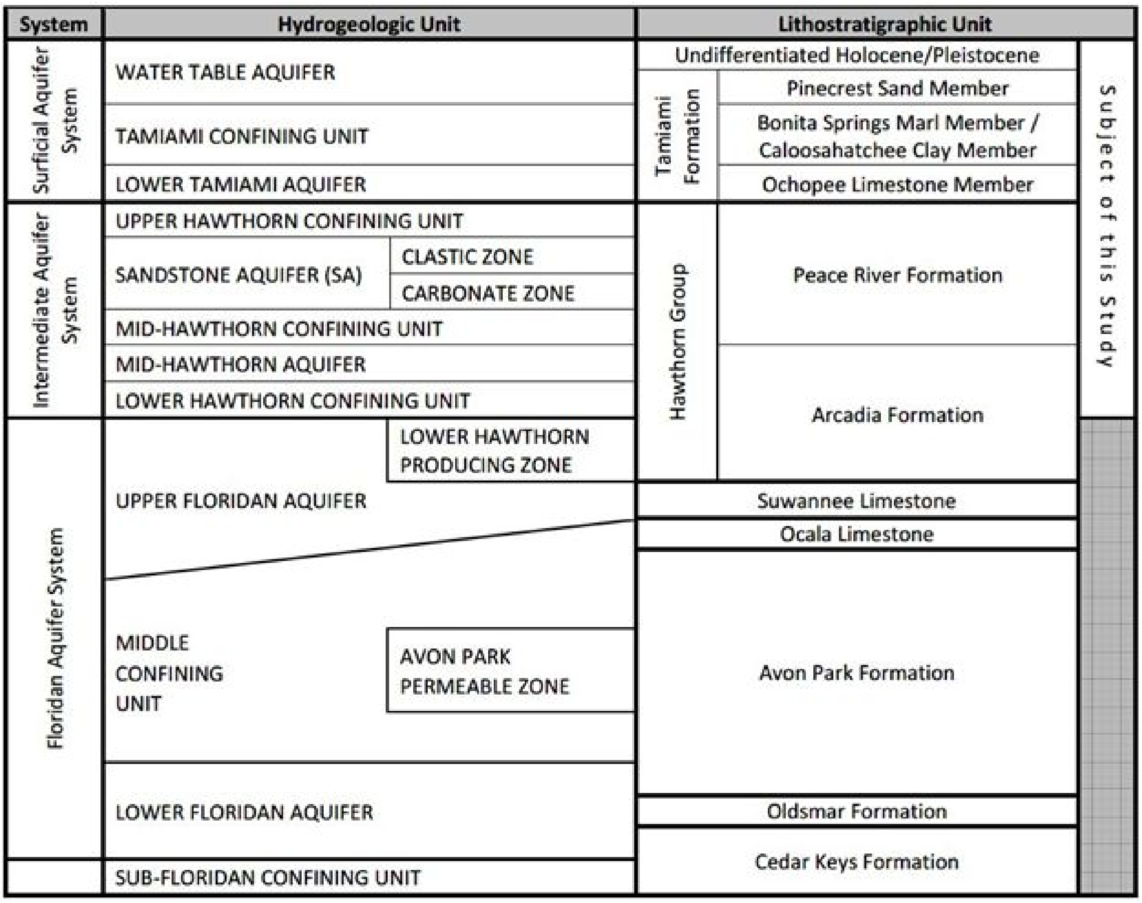


Figure 9. Generalized hydrogeologic and geologic units of the project area.

Lithology and Stratigraphy

In descending order, the stratigraphic units of significance in this region are the undifferentiated Holocene/Pleistocene sediments, the Tamiami Formation, and the Peace River and Arcadia Formations of the Hawthorn Group. The lithology of the undifferentiated surficial soil is highly variable. Medium- to fine-grained quartz sand, fossils, clays, and some freshwater limestone and marl are present.

The Tamiami Formation is composed of two units and four members. The upper confining unit is predominantly marl and clay while the lower water-bearing member is the Ochopee Limestone. The presence of these two units varies spatially. The Ochopee is absent in much of southwestern Hendry County. The confining unit is thicker in these areas and in portions of southwestern Lee and northwestern Collier counties.

Within the Hawthorn Group, the upper Peace River Formation consists of clays and carbonates interbedded with quartz sands. The Peace River Formation underlies the entire watershed area.

Beneath the Peace River Formation is the Arcadia Formation of the Hawthorn Group. It is predominately carbonate and occurs throughout the entire watershed area. The contact between the two formations may be distinct or gradational. The Arcadia Formation is primarily dolostone and limestone with beds of clay, quartz sand, and phosphate grains (Scott 1988).

Hydrogeology

The hydrogeology of the LWC Planning Area is complex. Lateral facies changes and variable bed thicknesses lead to large local variations in hydrogeologic units. The heterogeneous natures of the units and the sparse availability of data in places pose difficulties for regional-scale mapping.

Water Table Aquifer

The water table aquifer is composed primarily of quartz sand and shell with minor amounts of organic material. A dense limestone cap rock is present in some areas. The basal confinement is geographically variable. The water table aquifer is absent or insignificant in places within the LWC Planning Area. In the Tidal Caloosahatchee Subwatershed, the water table aquifer ranges in thickness between 10 and 30 feet (SFWMD 2015).

In general, a ‘water table aquifer’ is considered an unconfined unit extending from the water table to the first persistent confining unit. In the LWC Planning Area, the terminology more specifically refers to the permeable materials from the water table to the top of the Tamiami confining unit. Confinement between the water table aquifer and the underlying Lower Tamiami aquifer, however, is inconsistent. Where the Tamiami confining unit is absent or insignificant, the water table aquifer encompasses all permeable units above the upper Peace River confining beds.

Lower Tamiami Aquifer

The Lower Tamiami aquifer is predominantly sandy, biogenic limestone, and calcareous sandstone. It encompasses all the water-producing limestone and, in some areas, portions of the underlying permeable sand. The upper confinement (Tamiami confining unit) is absent or insignificant in some areas. In the northern portions of the area of interest, Charlotte County and beyond into the Southwest Florida Water Management District boundaries, reports typically do not distinguish subunits of the SAS. Throughout most of the study area, the lower permeable clay and fine-grained sands of the Peace River Formation provide basal confinement (Upper Hawthorn confining unit) to the Lower Tamiami aquifer. However, in some areas, this confinement is absent or insignificant. The Lower Tamiami aquifer is the most prolific aquifer in southeast Hendry County and all of Collier County. This aquifer supplies drinking water to several utilities and meets the demands of landscape, recreational, and agricultural irrigation wells.

Sandstone Aquifer

The Sandstone aquifer is contained entirely within the Peace River Formation of the Hawthorn Group and is part of the IAS. It is recharged by vertical seepage from overlying aquifers. The Sandstone aquifer typically occurs as two distinct permeable units, an upper clastic zone, and a lower carbonate zone. The Sandstone aquifer is composed of sandstone, sandy limestones, dolostones, and calcareous sands. These may be contiguous or separated by varying amounts of low permeability silt and clay. Where a confining unit is present, the Sandstone aquifer is separated from the Lower Tamiami aquifer by the lower permeable clays and dolosilts of the Peace River Formation (Upper Hawthorn confining unit). The Sandstone aquifer is separated from the underlying Mid-Hawthorn aquifer by low permeability clays and marls of the basal Peace River Formation (Mid-Hawthorn confining unit), which are present throughout the study area. The productivity of the Sandstone aquifer is highly variable, although it does provide for some domestic self-supply, a few utility wellfields, and some agricultural irrigation uses.

Mid-Hawthorn Aquifer

The Mid-Hawthorn aquifer is composed of biomicritic limestone, phosphate, shell, and lime mud. It lies within the Arcadia Formation of the Hawthorn Group. The Mid-Hawthorn aquifer is separated from the overlying Sandstone aquifer by the low permeable clays and marls of the basal Peace River Formation (Mid-Hawthorn confining unit). Where the Sandstone aquifer is absent or insignificant (**Figure 9**), the entire thickness of the Peace River Formation isolates the Mid-Hawthorn aquifer from the overlying SAS. The confinement from the underlying Lower Hawthorn producing zone consists of carbonate muds and terrigenous clays of the upper Arcadia Formation (Lower Hawthorn confining unit) and is present throughout the study area. Wedderburn et al. (1982) described the Mid-Hawthorn aquifer as a single aquifer composed of multiple thin permeable zones of limestone, dolomite, sandstone, and calcareous quartz sand interbedded with low permeability sands and clayey dolosilts. The Mid-Hawthorn aquifer is primarily recharged by the FAS, and typically reflects similar water quality and salinity to that of the FAS. For the most part, the use of the Mid-Hawthorn aquifer occurs in the western part of the project area.

Lower West Coast Aquifers MFL

In 2001, the SFWMD Governing Board adopted an MFL rule specifying that the minimum levels for the Lower Tamiami, Sandstone, and Mid-Hawthorn aquifers was the structural top of each aquifer. A violation of the criteria occurs when levels drop below the top of the uppermost geologic strata comprising the aquifer at any point in time.

A prevention strategy was adopted to prevent these aquifers from falling below the MFL. The prevention strategy identified maximum developable limits (MDLs) for these three aquifers. The MDL rules prohibit water uses from allowing the potentiometric heads within each aquifer to drop to less than 20 feet above the top of the uppermost geologic strata that comprises the aquifers at any point during a 1-in-10 drought condition. **Figure 10** presents a conceptualization of the MDL concept (Smith 2015).

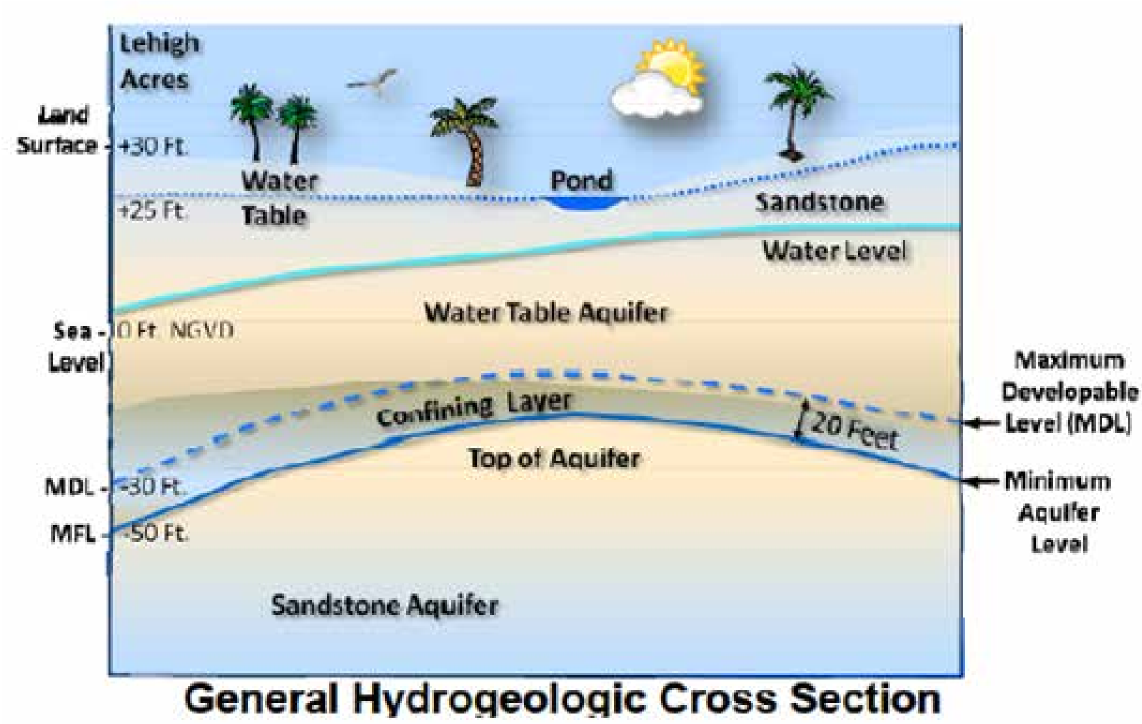


Figure 10. Illustration of MFLs and MDLs.
(Note: NGVD – National Geodetic Vertical Datum of 1929.)

SURFACE WATER-GROUNDWATER INTERACTIONS

In many ways, surface water and groundwater resources are highly interdependent in the LWC Planning Area. The percolation of rainfall recharges the water table. The vertical movement of groundwater from the water table recharges the underlying Lower Tamiami and Sandstone aquifers.

Surface water systems in the LWC function primarily as aquifer drains, since groundwater levels generally exceed the surface water elevations. The C-43 Canal, CRE, and Gulf of Mexico act as regional discharge points. Groundwater seepage provides a relatively small component of inflow to the Caloosahatchee, Orange, Imperial, and Estero rivers as well as base flows to wetland and slough systems.

During the wet season, some recharge to the SAS occurs from drainage canals, small lakes such as Lake Trafford, and low lying areas where stormwater levels temporarily exceed local groundwater levels (Knapp 1984, Smith and Adams 1988a, 1988b). The S-79 also provides a freshwater head to reduce saltwater intrusion into the water table aquifer, and helps maintain a higher water table in the lower region of the watershed (USACE 1957). Recent mapping by SFWMD (2014) indicates that groundwater within the water table aquifer of the Tidal Caloosahatchee Subwatershed is intruded by salt water (**Figure 11**).

Surface water management systems affect the quantity and distribution of recharge to the SAS. Surface water management systems affect aquifer recharge by diverting rainfall runoff from an area before it has time to percolate down to the water table. Once diverted, this water may contribute to aquifer recharge elsewhere in the system, supply a downstream consumptive use, lost to evapotranspiration, or discharged to tide.

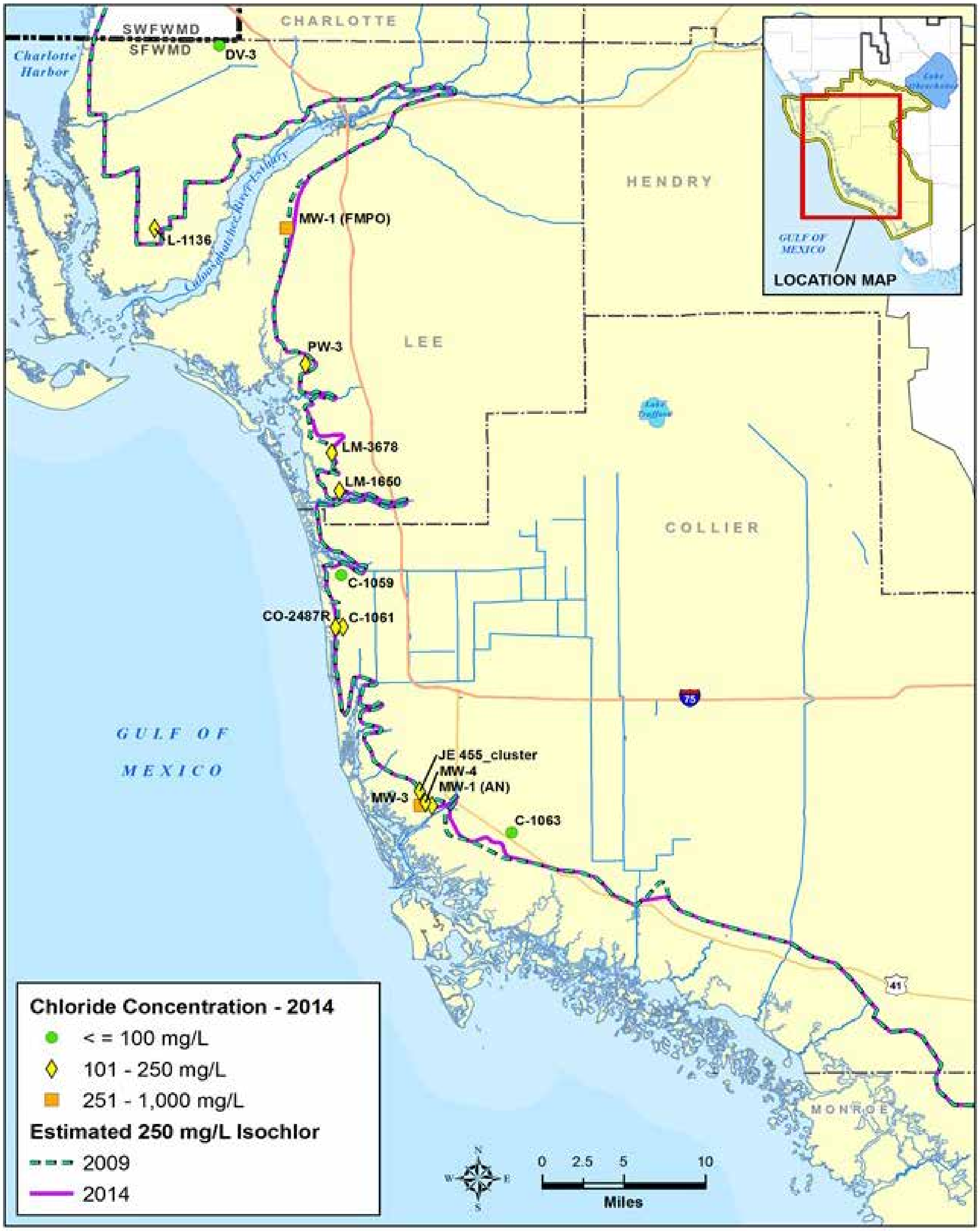


Figure 11. Estimated position of the saltwater interface within the water table aquifer in Collier and Lee counties in March–May 2014. (Source: *2017 Lower West Coast Water Supply Plan Update Appendices* [SFWMD 2017]. Well details are provided in Table E-1 of Appendix E of the *2017 Lower West Coast Water Supply Plan Update Appendices*.)

SURFACE WATER SYSTEMS

C-43 Canal

Historically, the Caloosahatchee River was sinuous river as discussed in **Chapter 2**. Today, the C-43 Canal has a total length of 41.6 miles (67 km). It conveys water released from Lake Okeechobee and runoff from the C-43 Watershed to the CRE. The C-43 Watershed is 931 square miles (2,413 km^2) in size and comprises 70% of the total area draining into the estuary (the Tidal Caloosahatchee Subwatershed accounts for the remaining 30%) (Qiu and Wan 2013).

Lake Okeechobee

Lake Okeechobee is the largest freshwater lake in the southern United States. It covers 730 square miles with an average depth of only 9 ft (2.7 m). More than 50% of the inflow to Lake Okeechobee comes from the Kissimmee River. The Kissimmee River begins at the southern end of Lake Kissimmee and receives surface water inflow from the upstream headwater lakes (Lakes Kissimmee, Cypress, and Hatchineha) and the Upper Chain of Lakes. The numerous small watersheds along the north shore of Lake Okeechobee contribute the rest of the inflow. Lake Okeechobee discharges to the east into the C-44 Canal, to the west the C-43 Canal, and to the south into the Everglades.

Changes in Lake Okeechobee Regulation Schedules

Lake Okeechobee is a central component of the C&SF Project. Regulatory releases from Lake Okeechobee are made at the Moore Haven Locks (S-77) at the head of the C-43 Canal. The regulation schedules for Lake Okeechobee are federally adopted by USACE. Discharges vary throughout the year and are primarily dependent upon the rainfall over the Lake Okeechobee Watershed. Discharges that occur through the S-79 structure are regulated and controlled by USACE. As the local sponsor for the C&SF Project, SFWMD interacts with USACE on a weekly basis to provide discharge (flow) recommendations to USACE. Ultimately, the USACE makes the final decision for the regulatory/flood control releases from the S-79 structure to the CRE.

Regulatory releases from Lake Okeechobee have been managed by USACE since the 1930s. Total discharges from S-77 and S-79 have varied over time depending on lake stage, regulation schedule, and surface water contributions from the watershed. From the early 1900s to mid-2000, the regulation schedules varied but were primarily calendar-based regulation schedules (SFWMD 2010). The first climate-based schedule, known as the Water Supply and Environment (WSE) Schedule, was adopted in July 2000. WSE incorporated climate outlooks and tributary hydrologic conditions into the operational guidance and decision making (USACE and SFWMD 1999).

An interim climate-based schedule, known as the 2008 Lake Okeechobee Regulation Schedule (LORS2008), was implemented by USACE to address safety concerns regarding the dike surrounding the lake. This schedule became operative in April 2008 and is the current regulation for Lake Okeechobee. LORS2008 is intended to operate the lake at lower levels while repairs to the dike are completed (SFWMD 2010). The operational stage range under LORS2008 is approximately one foot lower than the previous regulation schedule to reduce the risk that the lake's dike might fail. Regulatory releases are made by the USACE from Lake Okeechobee to the coastal estuaries per LORS2008 when releases south are not sufficient to manage lake stages. The C-43 Canal receives the bulk of these regulatory releases, often on top of high local basin runoff.

Adaptive Protocols for Lake Okeechobee Operations

Adaptive protocols were developed by SFWMD to provide operational guidance and a framework for making Lake Okeechobee release recommendations to USACE (SFWMD 2010). The adaptive protocols operational guidance considers multiple and competing needs of Lake Okeechobee and the C&SF Project. Within the constraints of the federal water control plan (USACE 2008), the goal and objective of implementing adaptive protocols is to improve flood protection, water supply, and ecosystems benefits. Adaptive Protocols for Lake Okeechobee Operations were first developed in 2003 to aid release decisions associated with the 2000 WSE Schedule. These adaptive protocol guidance recommendations were later modified for compatibility with LORS2008 in September 2010 and August 2012.

Adaptive protocols provide guidance for regulatory releases from Lake Okeechobee when the lake is within the Low and Baseflow subbands of LORS2008. The adaptive protocols also provide guidance for environmental water supply deliveries to the CRE when the lake stage is within the Beneficial Use Subband of LORS2008. SFWMD provides recommendations developed through the adaptive protocols to USACE for consideration in managing the lake within the constraints of the existing authorizations, infrastructure, and operational flexibility of LORS2008. One of the intended environmental benefits is to improve the salinity within the CRE without adversely affecting water supply performance for permitted users and without increasing Lake Okeechobee MFL exceedances.

FRESHWATER INFLOWS

Flows over S-79

The S-79 structure was built in 1965 to prevent brackish water from moving upstream into the C-43 Canal and to maintain the surface water stage and groundwater table in the upstream watershed. Freshwater discharge at S-79 represents the combined contribution of rainfall-driven runoff from the East and West Caloosahatchee subwatersheds as well as releases from Lake Okeechobee. During the wet season, water may be released to regulate surface water levels within Lake Okeechobee. In the dry season, water is released to the CRE, when available, to help mitigate saltwater intrusion and maintain preferred salinity levels in the estuary. Surface water from Lake Okeechobee may periodically be released from the lake and discharged to the estuary when heavy rainfall causes the lake stages to exceed the approved regulation schedule.

A water year runs from May 1 to April 30 of the subsequent year. The average annual long-term total inflow through S-79, from Water Year 1997 (WY1997; May 1, 1996–April 30, 1997) to WY2015, was 1.409×10^6 acre-feet (ac-ft), which is approximately 79% of total inflow to the estuary; the Tidal Caloosahatchee Subwatershed contributed the remaining 21% (Zheng et al. 2016). As stated earlier, Lake Okeechobee was operated with two different regulation schedules since 2000 when the minimum flow of 300 cfs at S-79 was developed: the WSE Schedule (July 2000 to March 2008) and LORS2008 (April 2008 to present). In order to identify the difference in flow characteristics at S-79 under the two different operation schedules, the flow statistics (mean and standard deviation) and flow distribution were analyzed based on daily flow from WY1997 to WY2015 (**Table 3** and **Figures 12** and **13**).

Table 3. Mean and standard deviation for daily flow at S-79.

Time Period	Operation Schedule	Mean	Standard Deviation	Percent of Time Daily Flow < 300 cfs
7/1/2000 – 3/31/2008	WSE	2,065	2,996	39.1%
4/1/2008 – 4/30/2016	LORS2008	1,790	2,346	23.5%

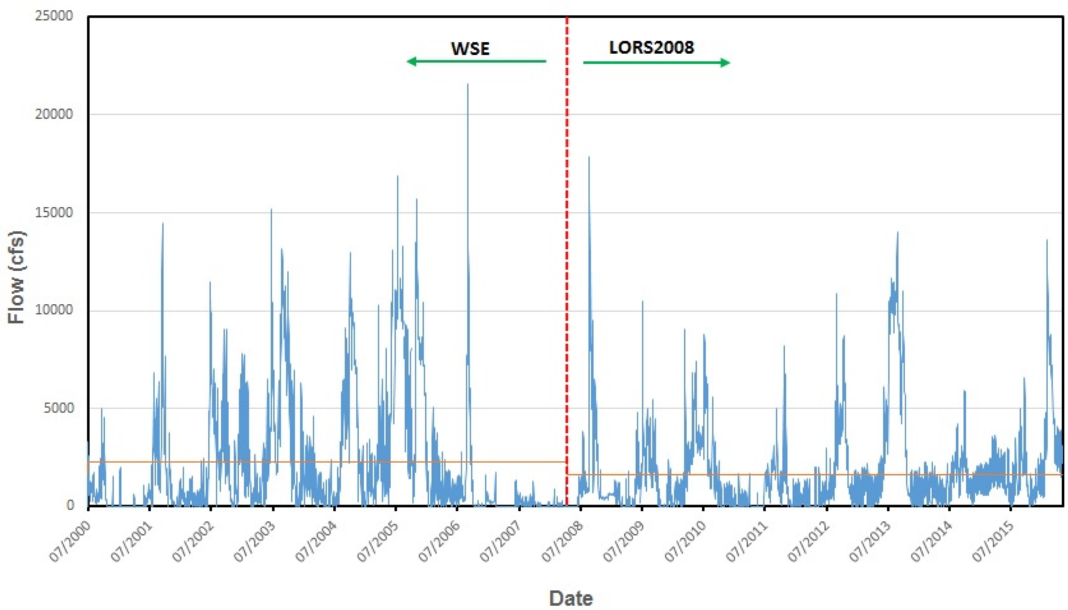


Figure 12. Daily flow over S-79 from June 1, 2000, to April 2016.
(Note: Orange horizontal line represents the mean value.)

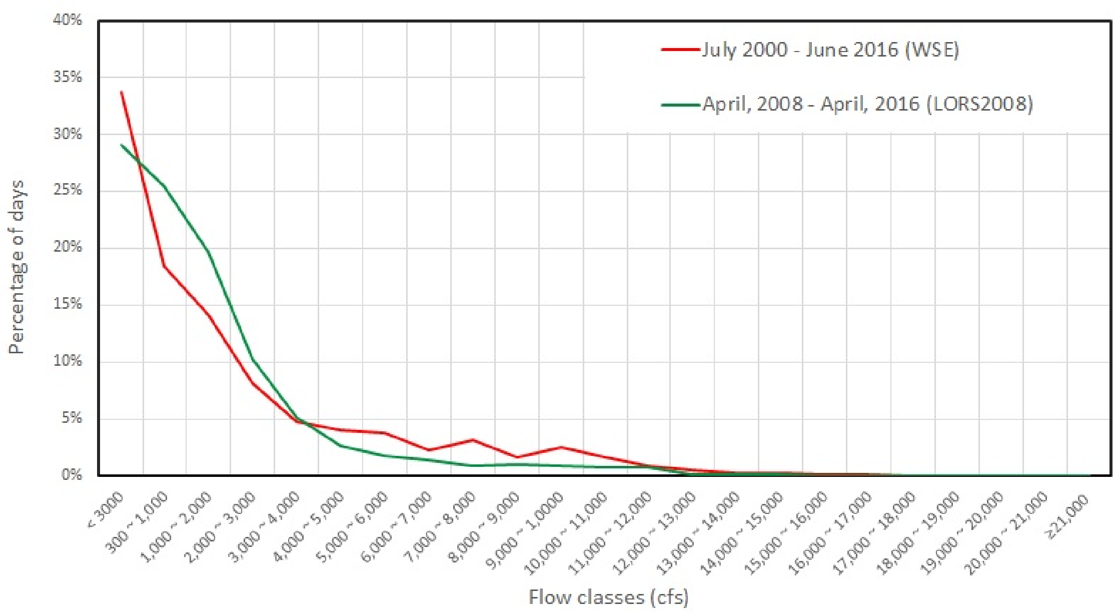


Figure 13. Frequency distribution of daily flow at S-79.

The mean and standard deviation of daily flow released through S-79 under LORS2008 was 1,790 and 2,346 cfs, respectively, both less than those values under WSE (275 cfs less in mean and 650 cfs less in standard deviation). In other words, S-79 flow generally appeared lower with less fluctuation under LORS2008 compared with the flow under WSE. In addition, in about 39.1% of days, S-79 flow was less than 300 cfs under WSE, which significantly decreased to 23.5% with LORS2008 (**Table 3**). Under LORS2008, S-79 released flow with a range of 300 to 4,000 cfs in a much higher percentage time (65.1%) compared with that under WSE (42.01%) (**Figure 13**). Statistically, over the period of record of 2000 to 2016, S-79 flow was in the low flow range (< 300 cfs) and high flow range (> 4,000 cfs) for 34.9% of days under LORS2008 versus 57.9% of days under WSE.

It has been documented that inflow at S-79 positively responded to rainfall, and about 30% occurred in the dry season while 70% occurred in the wet season (Zheng et al. 2016). Thus, climate is another factor causing the changes of flow distribution at S-79. In fact, the operation of Lake Okeechobee depends heavily on the amount of runoff to the lake from the upstream watershed resulting from local rainfall.

C-43 Watershed Inflow

Between S-77 and S-79, the C-43 Watershed covers the drainage area of approximately 596,354 ac. Based on the daily flow data from S-79 between WY1996 to WY2015, the C-43 Watershed contributed about 48% (0.847×10^6 ac-ft) of average annual total inflow into the estuary (Zheng et al. 2016). The daily flow has a mean value of 1,203 cfs with a standard deviation of 1,908 cfs. About 19.2% of inflow occurred in the dry season (November to April) while 80.8% occurred in the wet season (May to October).

Inflows from Lake Okeechobee

From WY1996 to WY2015, about 31.6% (0.562×10^6 ac-ft) of average annual total inflow into the estuary was from Lake Okeechobee (Zheng et al. 2016). The flow was almost evenly distributed between the wet (51.3%) and dry (48.7%) seasons. The mean daily flow released from the lake to the estuary was 839.5 cfs with a standard deviation of 1,671 cfs.

Tidal Caloosahatchee Subwatershed Tributaries and Contribution

The Tidal Caloosahatchee Subwatershed has a drainage area of 413.6 square miles (264,705.5 ac) from S-79 to Shell Point. It has a number of tributaries that drain water into the CRE. Those tributaries are (1) Telegraph Creek, (2) Orange River, (3) Popash Creek, (4) Billy's Creek, (5) Hancock Creek, (6) Whiskey Creek/Canal L, (7) Trout Creek, (8) Stroud Creek, (9) Daughtrey Creek, (10) Powell Creek, (11) Marshpoint Creek, (12) Bayshore Creek, (13) Cape Coral Canal System (San Carlos/Courtney Canal, Plato Canal, Mackinac Canal, and Meade/Honolulu Canal), (14) Manuels Branch, (15) Winkler Canal, (16) Deep Lagoon, and (17) other small canals and ditches (**Figure 14**).

Stage and flow at the outlet of tributaries (1) through (5) listed above were monitored from 2008 to March 2013 through the joint efforts of the United States Geological Survey (USGS), Florida Department of Environment Protection (FDEP), and SFWMD. Lee County has monitored the Whiskey Creek/Canal L since 1991. **Figure 14** also shows the location of the 5 tributaries listed above along with Whiskey Creek. The flow at these six stations represents approximately 50% of the total contributions from the Tidal Caloosahatchee Subwatershed. To quantify the freshwater inflow from the Tidal Caloosahatchee Subwatershed, a watershed model was developed. The model was calibrated and verified using the measured flow at the six stations mentioned above and the flow data from Shell Point and Marker 52 (**Figure 14** and **Appendix D**).

The model was used to conduct a long-term simulation from 1967 to 2012. During this period of record (POR), the simulation results show the average inflow for all seasons was approximately 430 cfs. The average inflow during the dry season was 245 cfs while the wet season had an average inflow of 613 cfs. Inflow from the Tidal Caloosahatchee Subwatershed was about 20% of total inflow to the CRE while the remaining 80% of the inflow was from the C-43 Watershed and Lake Okeechobee released through S-79. Groundwater contributions from the Tidal Caloosahatchee Subwatershed are small during the dry season (23 cfs, approximately 1.6%) and more than triple during the wet season (76 cfs, approximately 2.7%).

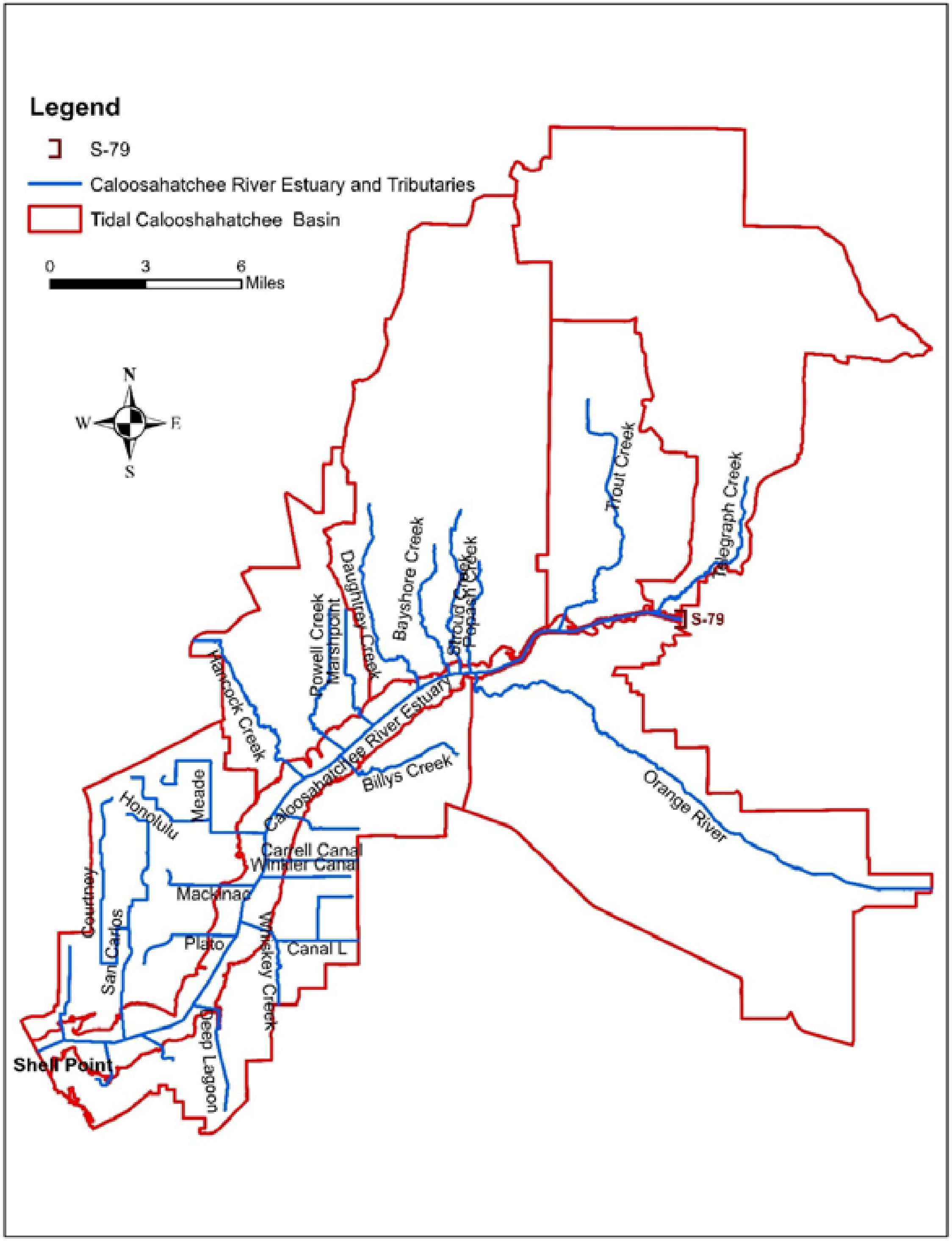


Figure 14. Tidal Caloosahatchee Subwatershed boundary, CRE, and tributaries.

ENVIRONMENTAL PROBLEMS RELATED TO HYDROLOGY

Many of the ecological problems in the CRE stem from widely fluctuating salinity resulting from high seasonal and interannual variation in discharge that occurs at the Franklin Lock and Dam (S-79 structure) combined with the channelization of the river. These widely fluctuating discharges are a result of the watershed changes and structural alterations that have occurred within the freshwater and estuarine portions of the watershed.

Wet Season

During the wet season, watershed runoff from the basins upstream of the S-79 structure, supplemented by regulatory releases from Lake Okeechobee, drastically reduce salinity levels over most of the estuary and darkens the water restricting the depth of light penetration. Large volumes of fresh water during the wet season can flush most of the salt water from the estuary. Effects of high discharges were acknowledged even before the S-79 structure was built (University of Miami 1954, Phillips and Springer 1960, Gunter and Hall 1962).

Flow records from May 1966 to May 2016 indicate that there is considerable seasonal variation in median daily flows at the S-79 structure (**Figure 15**). The wet season median daily flow of 1,294 cfs from the S-79 structure was about five times greater than the dry season median daily flow of 249 cfs. During June and September, the wettest months of the wet season, 25% of the flows measured on a particular day of the year may exceed 3,700 cfs (SFWMD 2014). During the wet season, regulatory releases from Lake Okeechobee are required to provide flood protection. These additional discharges from the lake can exacerbate the already low salinity conditions in the estuary and adversely affect marine species (oysters, seagrasses, etc.).

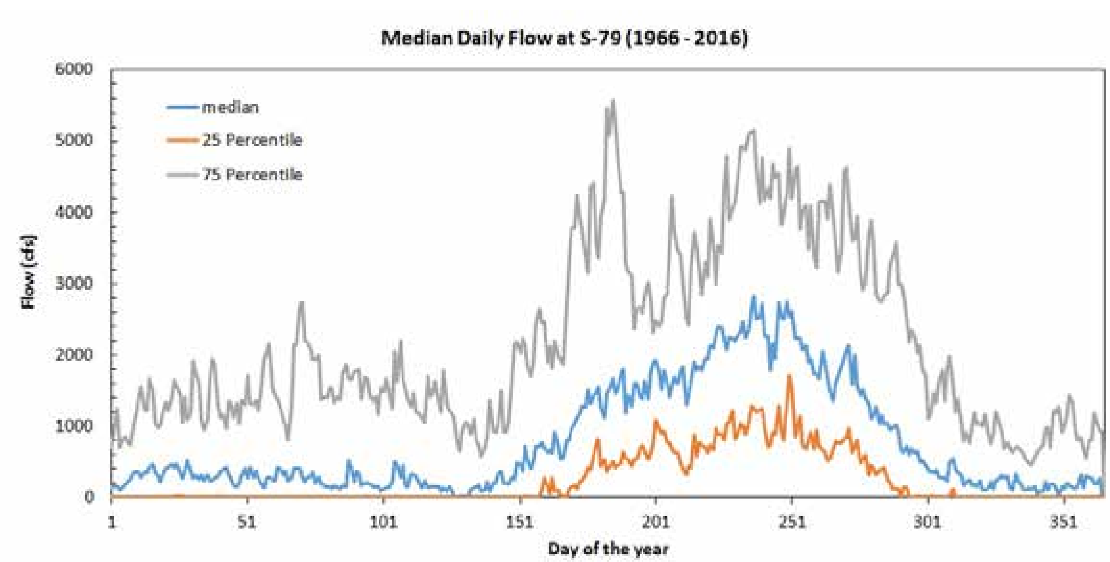


Figure 15. Median daily discharge at the S-79 structure May 1966–May 2016. (Note: Also shown are the 25th and 75th percentiles.)

Dry Season

During the dry season, freshwater inflow can be so low that salt water migrates up to the S-79 structure, truncating the salinity gradient within the estuary. Tape grass, *Vallisneria americana*, is an important upper estuarine SAV species and is sensitive to saltwater intrusion or high salinity conditions. During low flow periods, this habitat-forming species can become stressed or experience mortality if high salinity conditions persist for too long in the upper CRE. At very low flows during the dry season, some species, notably juvenile bay anchovies (*Anchoa mitchilli*) and their mysid (Mysida) prey, became impinged on the S-79 structure and are thus prevented from moving further upstream (Tolley et al. 2010). Habitat compression occurs as these and other species became concentrated in the narrow portion of the river just downstream of the structure. The crowding of organisms into a relatively confined space (habitat compression; Crowder 1986, Copp 1992, Eby and Crowder 2002) may result in increased predation and competition for limited food resources. Some organisms may be forced to utilize habitat that is physiologically suboptimal, which may reduce growth and survival (Petersen 2003). Many estuaries have water control structures (e.g. dams) that regulate freshwater inflow. These structures block upstream movement of planktonic organisms with reduced inflow and serve as barriers to adult fish migration (impingement; Peebles and Greenwood 2009). Impingement against a water control structure such as S-79 can exacerbate habitat compression. For more information on responses of zooplankton and a multitude of indicators to low freshwater inflow during the dry season see **Chapter 5** and **Appendix A**.

Problems with High Variance in Freshwater Inflows

Alterations to the CRE MFL Watershed have resulted in wide variations in freshwater inflows. Fluctuations in freshwater inflow over time scales ranging from weeks to years have altered salinity regimes and impacted the ecology of the CRE (Chamberlain and Doering 1998, Barnes 2005). Research conducted since the S-79 structure was put into operation (Chamberlain and Doering 1998, Doering et al. 2002, Volety et al. 2009) confirmed that high discharges to the CRE can reduce salinity in the lower estuary (at the seaward end) to levels low enough to cause mortality of organisms that cannot escape (e.g. oysters and seagrass). Conversely, a lack of freshwater discharge during the dry season allows salinity to increase in the upper estuary (near S-79) to levels high enough to cause mortality to freshwater organisms (e.g. *Vallisneria*). Truncation of the salinity gradient occurs during these extreme high and low flow events affects organisms at both ends of the estuary. Much of the research substantiating the ecological problems associated with widely fluctuating freshwater flows includes a broad spectrum of marine organisms in the CRE (**Appendix A**).

The project implementation report for the Caloosahatchee River (C-43) West Basin Storage Reservoir (C-43 Reservoir) identified the cause of the high variance in discharge is the lack of regional storage within the watershed (USACE and SFWMD 2010). The purpose of the reservoir is to reduce some of these wide variations in freshwater inflows. It is designed to help promote a more balanced and healthy salinity regime for the CRE by providing more consistent flows during periods of low flow (dry season) while reducing a portion of high flow discharges that typically occur during the wet season. For more information about the C-43 Reservoir and the MFL recovery strategy please see **Chapter 10**.

CHAPTER 4: WATER RESOURCE FUNCTIONS

WATER RESOURCE FUNCTIONS AND SIGNIFICANT HARM

Water resource functions of surface waterbodies and aquifers include flood control, water quality protection, water supply and storage, fish and wildlife habitat, navigation, and recreation. Additionally, the Water Resource Implementation Rule (Chapter 62-40, F.A.C.) requires consideration of natural seasonal fluctuations in water flows or levels, non-consumptive uses, and the environmental values listed below which are associated with coastal, estuarine, riverine, spring, aquatic, and wetlands ecology (Rule 62-40.473, F.A.C.):

- Recreation in and on the water
- Fish and wildlife habitats and the passage of fish
- Estuarine resources
- Transfer of detrital material
- Maintenance of freshwater storage and supply
- Aesthetic and scenic attributes
- Filtration and absorption of nutrients and other pollutants
- Sediment loads
- Water quality
- Navigation

Determining which resource functions to consider in establishing MFLs requires a comprehensive look at the sustainability of the resource itself as well as its role in sustaining overall regional water resources. This chapter provides a detailed description of the relevant water resource functions of the CRE.

CRE WATER RESOURCE FUNCTIONS

The primary functions of the CRE considered in the development of its MFL include fish and wildlife habitats, estuarine resources, water supply, recreation, navigation, and flood control.

Fish and Wildlife Habitats

Douglass (2013) reported the presence of rooted aquatic vegetation in the CRE that followed a salinity gradient from the upper estuary, which is predominantly fresh water, to the lower estuary, which is predominantly marine. Aquatic plant communities serve as habitats and/or food sources for a number of aquatic organisms (Rozas and Hackney 1983, Beck et al. 2001, Heck et al. 2003, Rozas and Minello 2006). In the CRE, these organisms include fish, shellfish, aquatic mammals, freshwater turtles, birds, epiphytes, and aquatic invertebrates (CHNEP 2016, FWC 2016, USFWS 2016). Aquatic plants also stabilize sediments, attenuate wave action, improve water clarity, remove nutrients, such as nitrogen and phosphorus, and increase or decrease dissolved oxygen concentrations depending on abundance and the availability of light (Abal and Dennison 1996, Hemminga and Duarte 2000, Farve et al. 2004, Bradley and Houser 2009, Oguz et al. 2013, Anderson et al. 2011, Seitz et al. 2014, CHNEP 2016, IFAS 2016).

Hunt and Doering (2013) reported recent research and field studies document the use of the estuary as a nursery for several species of fish and invertebrates including blue crab (*Callinectes sapidus*), bull shark (*Carcharhinus leucas*), and smalltooth sawfish (*Pristis pectinata*). Portions of the Caloosahatchee River are designated as critical habitat for the smalltooth sawfish (NMFS 2009). The National Marine Fisheries website lists the CRE as essential habitat for juvenile brown shrimp (*Farfantepenaeus aztecus*), juvenile gray snapper (*Lutjanus griseus*), juvenile pink shrimp (*Farfantepenaeus duorarum*), adult and juvenile red drum (*Sciaenopsis ocellatus*), adult and juvenile Spanish mackerel (*Scomberomorous maculatus*), and juvenile stone crab (*Menippe mercenaria*) (USACE and SFWMD 2010).

State and federal lists of threatened and endangered species, and state species of special concern, that are believed to, or are known to, occur in the open waters and/or wetlands of the CRE MFL Watershed are given in **Table 4** (FWC 2016, USFWS 2016). Some of these species have been observed utilizing the CRE as a food source and breeding area, including the West Indian manatee (*Trichechus manatus latirostris*), brown pelican (*Pelecanus occidentalis*), little blue heron (*Egretta caerulea*), reddish egret (*Egretta rufescens*), snowy plover (*Charadrius nivosus* [*Charadrius alexandrine*s]), tricolor heron (*Egretta tricolor*), and white ibis (*Eudocimus albus*) (CHNEP 2016).

All federally listed species that occur in Florida are included on Florida's imperiled species list as federally-designated endangered (FE) or federally-designated threatened (FT) species. Florida's listing designations for fauna are currently state-designated threatened (ST) or species of special concern (SSC). Florida does not have an endangered species designation for fauna. The SSC designation will be phased out by the end of 2017 and SSC species will either be changed to ST or they will be delisted, in accordance with the intent of Chapter 68A-27, F.A.C. This designation change will not occur until management plans for these species are completed and approved. All future Florida fauna listings will be designated as ST.

Table 4. Imperiled species occurring in open waters or wetlands of the CRE MFL Watershed. [a]

Common Name	Species	Florida Listing Status [b]	United States Listing Status [b]
Fish			
Gulf Sturgeon	*Acipenser oxyrinchus desotoi*	FT	FT
Mangrove Rivulus	*Kryptolebias marmoratus*	SSC [c]	
Smalltooth Sawfish	*Pristis pectinata*	FE	FE
Birds			
American Oystercatcher	*Haematopus palliatus*	SSC [d]	
Audubon's Crested Caracara	*Polyborus plancus audubonii*	FT	FT
Black Skimmer	*Rynchops niger*	SSC [d]	
Brown Pelican	*Pelecanus occidentalis*	SSC [c]	
Everglade Snail Kite	*Rostrhamus sociabilis plumbeus*	FE	FE
Florida Sandhill Crane	*Grus canadensis pratensis*	ST	
Least Tern	*Sterna antillarum*	ST	
Limpkin	*Aramus guarauna*	SSC [c]	
Little Blue Heron	*Egretta caerulea*	SSC [d]	
Piping Plover	*Charadrius melodus*	FT	FT
Red-cockaded Woodpecker	*Picoides borealis*	FE	FE
Reddish Egret	*Egretta rufescens*	SSC [d]	
Roseate Spoonbill	*Platalea ajaja*	ST	
Snowy Egret	*Egretta thula*	SSC [c]	
Snowy Plover	*Charadrius nivosus (Charadrius alexandrinus)*	ST	
Southeastern American Kestrel	*Falco sparverius paulus*	ST	
Tricolored Heron	*Egretta tricolor*	SSC [d]	
White Ibis	*Eudocimus albus*	SSC [c]	
Wood Stork	*Mycteria americana*	FT	FT
Mammals			
Florida Bonneted Bat	*Eumops floridanus*	FE	FE
Florida Panther	*Puma (=Felis) concolor coryi*	FE	FE
Sanibel Island Rice Rat	*Oryzomys palustris sanibeli*	ST	
Shermans Short-tailed Shrew	*Blarina carolinensis shermani*	SSC [d]	
West Indian Manatee	*Trichechus manatus latirostris*	FE	FE
Reptiles			
American Crocodile	*Crocodylus acutus*	FT	FT
American Alligator	*Alligator mississippiensis*	FT(S/A)	FT(S/A)
Eastern Indigo Snake	*Drymarchon corais couperi*	FT	FT
Green Sea Turtle	*Chelonia mydas*	FE	FT
Hawksbill Sea Turtle	*Eretmochelys imbricata*	FE	FE
Kemp's Ridley Sea Turtle	*Lepidochelys kempii*	FE	FE
Leatherback Sea Turtle	*Dermochelys coriacea*	FE	FE
Loggerhead Sea Turtle	*Caretta caretta*	ST	FT
Invertebrates			
Miami Blue Butterfly	*Cyclargus thomasi bethunebakeri*	FE	FE

a. Source: FWC 2016, USFWS 2016.

b. Key to Listing Status: FE – federally-designated endangered species, FT – federally-designated threatened species, FT(S/A) – federally-designated threatened species due to similarity of appearance with another listed species; listed for its protection (United States), ST – state-designated threatened species, and SSC – species of special concern.

c. This species will be delisted once a management plan is completed and approved.

d. The listing status for this species will change from SSC to ST once a management plan is completed and approved.

Estuarine Resources

The CRE MFL Watershed contains approximately 158,606 wetland ac and the CRE itself contains approximately 16,715 ac of wetlands and open water habitat. Some of these wetlands have been classified as fragile coastal wetlands by the Florida Natural Areas Inventory as part of its *Florida Forever Conservation Needs Assessment* (FNAI 2016) (**Figure 16**). The wetlands of the CRE include open waters (some deepwater areas), marshes, mangroves, and forested and shrub wetlands (NWI 2016). These varied components of the CRE ecosystem make it a highly productive estuary. The wetlands of the CRE are important foraging and nursery grounds for faunal species, including some commercially and recreationally important or endangered species as noted above.

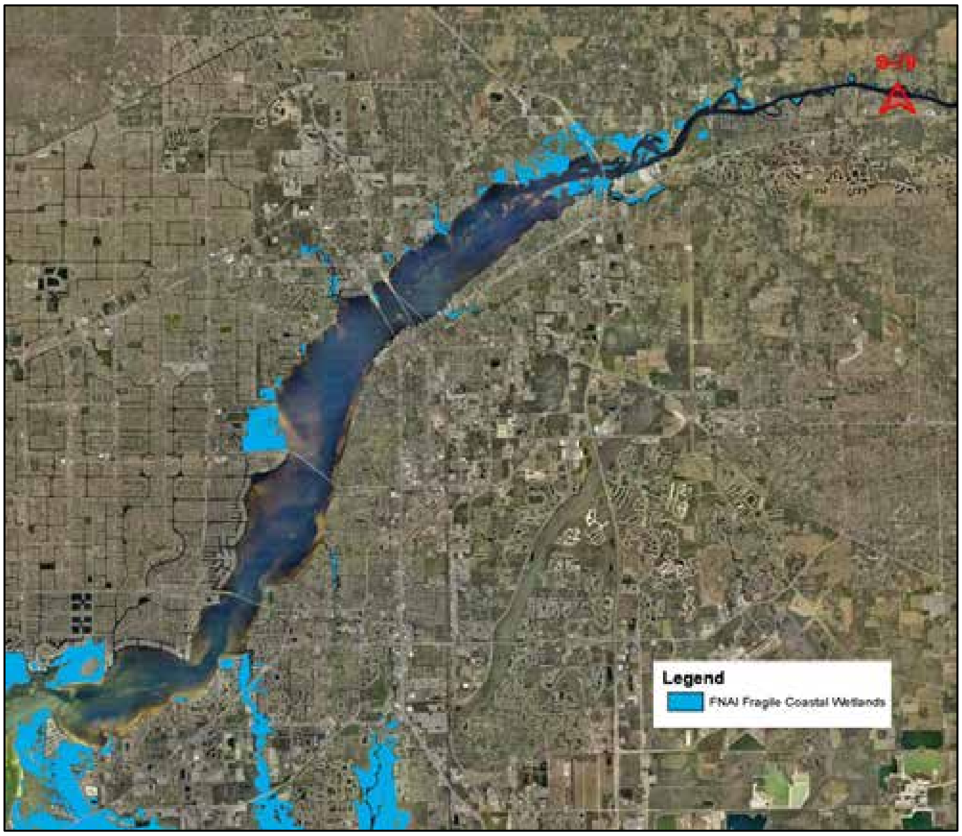


Figure 16. Fragile coastal wetlands in the CRE MFL Watershed (FNAI 2016).

Gosselink and Turner (1978) argued that the hydrologic characteristics of wetlands influence four ecosystem attributes: species composition of the plant community, primary productivity, organic deposition and flux, and nutrient cycling. The major "hydrodynamic characteristics" that they proposed were water inputs, water outputs, type of water flow, and hydropulses (i.e., seasonality). Maintaining appropriate water levels and flows in the CRE to sustain wildlife, and the vegetated habitats that support them, requires careful attention to the timing and quantity of freshwater inflows to the CRE.

Submerged Aquatic Vegetation in the CRE

Submersed aquatic vegetation (SAV) varies throughout the CRE (Hoffacker 1994, Chamberlain and Doering 1998). Its distribution and abundance varies in response to salinity, light penetration, and the amount of freshwater input (Hoffacker 1994, Chamberlain et al. 1995, Doering et al. 1999). SAV has been monitored throughout the CRE since 1998, and as part of the Comprehensive Everglades Restoration Plan (CERP) Restoration Coordination and Verification Program (RECOVER 2014) since 2004.

From 1998 to 2013, the dominant species in the upper estuary (Beautiful Island to Fort Myers) was *Vallisneria americana*, a low salinity tolerant tape grass. **Figure 18** shows the percent cover of this species from 1998 to 2013. Lush beds of *Vallisneria* were present in the upper estuary in the late 1990s (RECOVER 2014). However, the percent cover of *Vallisneria* varied significantly during the 1998–2013 POR. A loss of *Vallisneria* occurred during a severe drought in 2000–2001, but partial reestablishment occurred from 2004 to 2006. Since 2006, *Vallisneria* has been sparse to non-existent after repeated drought events in 2007–2008 and 2011. This species is an important indicator for the MFL reevaluation because of it is sensitive to low freshwater inflows and subsequent high salinity conditions. For more detailed information regarding *Vallisneria* studies and modeling conducted as part of this MFL reevaluation, see Component Studies 7 and 8 in **Appendix A**.

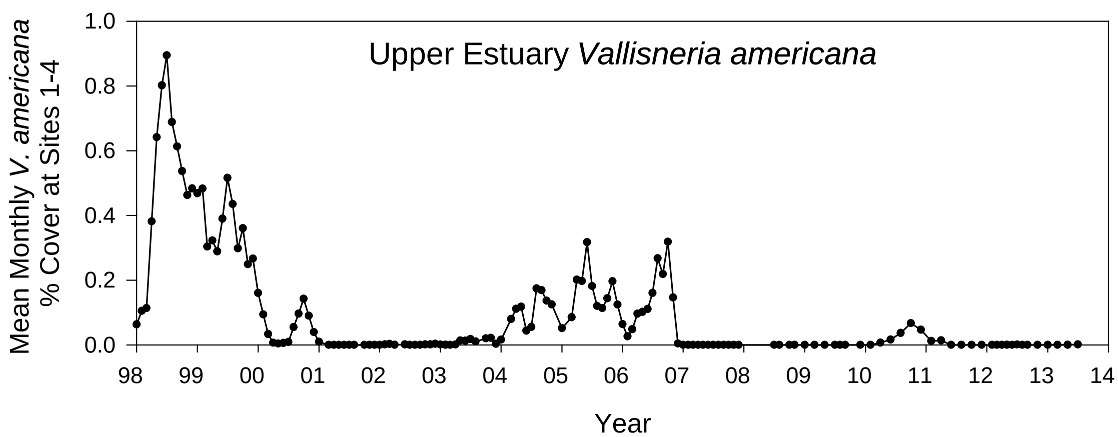


Figure 17. *Vallisneria americana* percent cover (1.0 = 100%) in the upper CRE from 1998 to 2013.
(Notes: These are mean values from three to four SAV monitoring sites in the upper estuary region. Source: RECOVER 2014.)

In the middle estuary (Fort Myers to Shell Point), *Halodule wrightii* (shoal grass) is the dominant species. **Figure 18** shows the percent cover of this species from 2004 to 2013. *Halodule* was absent in the middle estuary from 2004 to 2007, which was a period of low salinity caused by several hurricanes in 2004 and 2005. *Halodule* is vulnerable to stress from low salinity (high freshwater discharge) conditions.

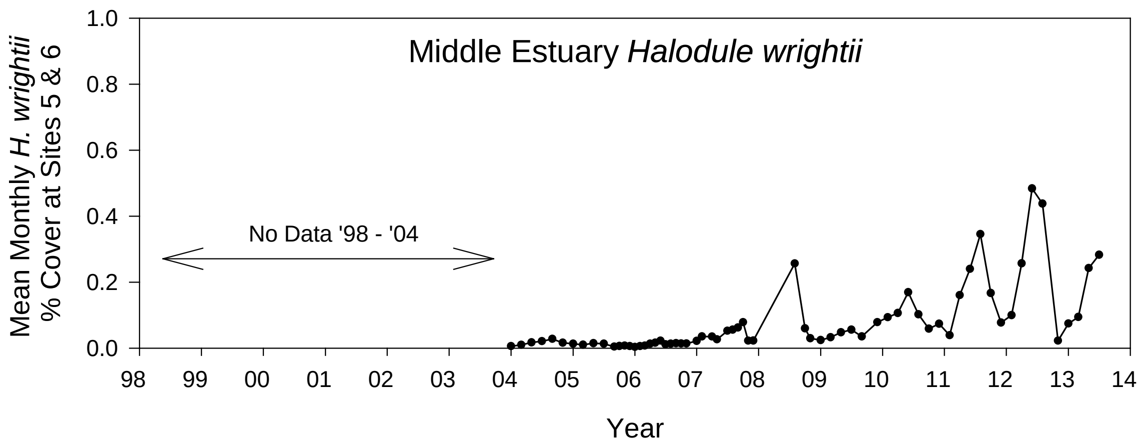


Figure 18. *Halodule wrightii* percent cover (1.0 = 100%) in the middle CRE from 2004 to 2013. (Notes: These are mean values from two SAV monitoring stations in the middle estuary region. Source: RECOVER 2014.)

The lower estuary (Shell Point to San Carlos Bay), where the highest salinity conditions occur, is dominated by *Halodule wrightii* (shoal grass) and *Thalassia testudinum* (turtle grass). **Figure 19** shows the percent cover of these two species from 2004 to 2013. Since 2013, the majority of SAV, in the form of seagrass, occurs in the lower estuary (**Figure 20**).

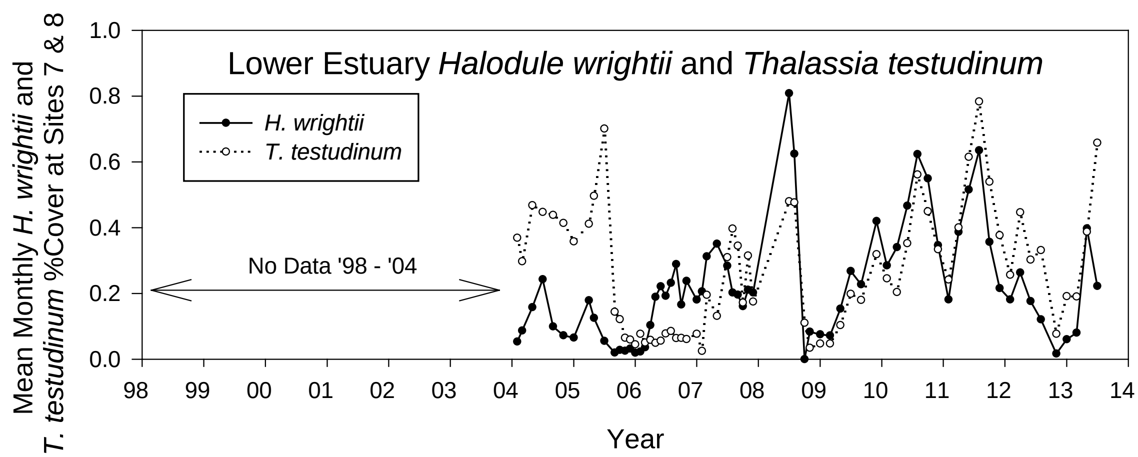


Figure 19. *Halodule wrightii* and *Thalassia testudinum* percent cover (1.0 = 100%) in the lower CRE (San Carlos Bay) from 2004 to 2013. (Notes: These are mean values from two SAV monitoring stations in the lower estuary. Source: RECOVER 2014.)

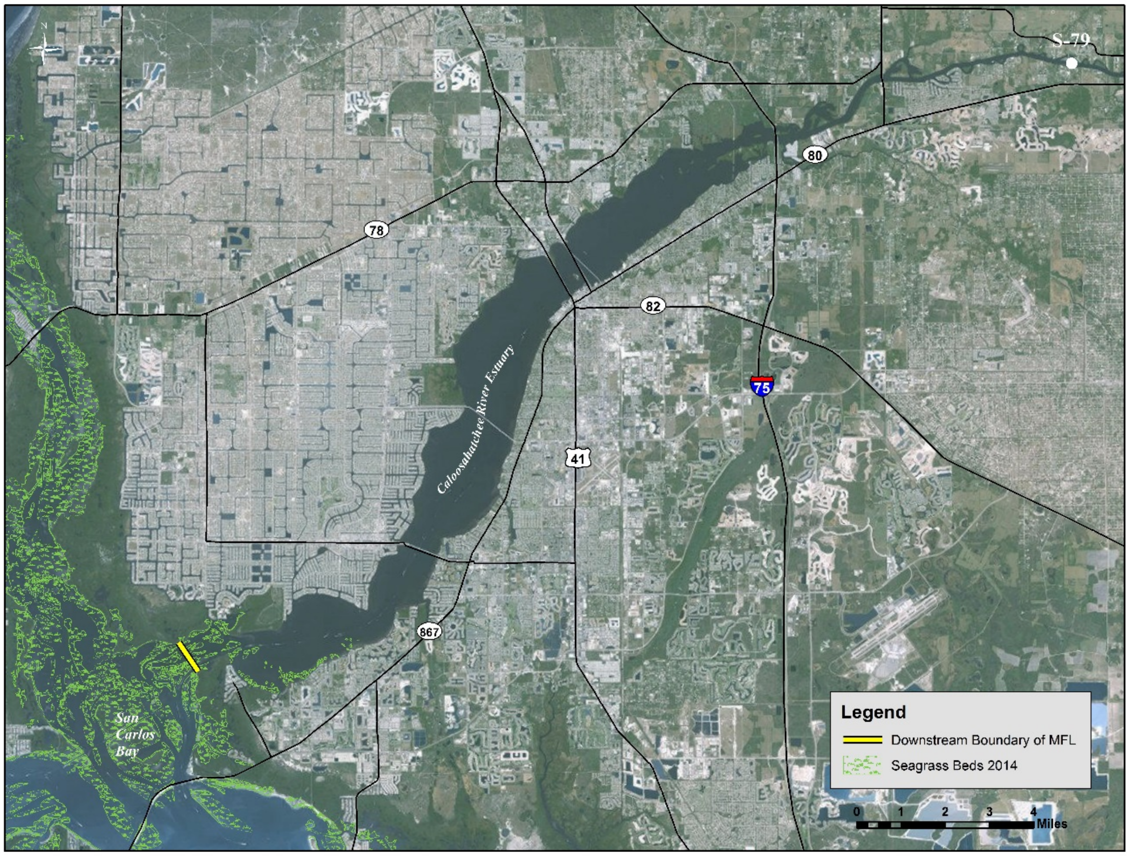


Figure 20. SAV (seagrass) in the CRE in 2014 (RECOVER monitoring).

Oysters in the CRE

Another important resource monitored in the CRE are eastern oysters (*Crassostrea virginica*). The oyster is an important ecological indicator because it integrates conditions in overlying water over time (RECOVER 2014). Oysters are found in the middle to lower CRE between Cape Coral and San Carlos Bay (**Figure 21**). **Figure 22** shows the trend in live oyster density in the lower CRE from Water Year 2016 (WY2006; May 1, 2015–April 30, 2016) through WY2017 (Buzzelli et al. 2018). Seasonally averaged live oyster density at this location varied from 500 to 3,500 oysters per square meter (oysters/m^2) from WY2006 to WY2017. Oyster density reached the maximum in the WY2013 dry season before decreasing to ~1,500 oysters/m^2 in WY2015 and WY2016. There appeared to be a slight increase in average live oyster density in WY2017 (> 2,000 oysters/m^2). Overall, oyster density was similar between the dry and wet seasons. For more detailed information regarding assessment of oysters within the CRE conducted as part of this MFL reevaluation, see Component Study 9 in **Appendix A**.

Figure 21. Oyster beds in the CRE in 2010 (RECOVER monitoring).

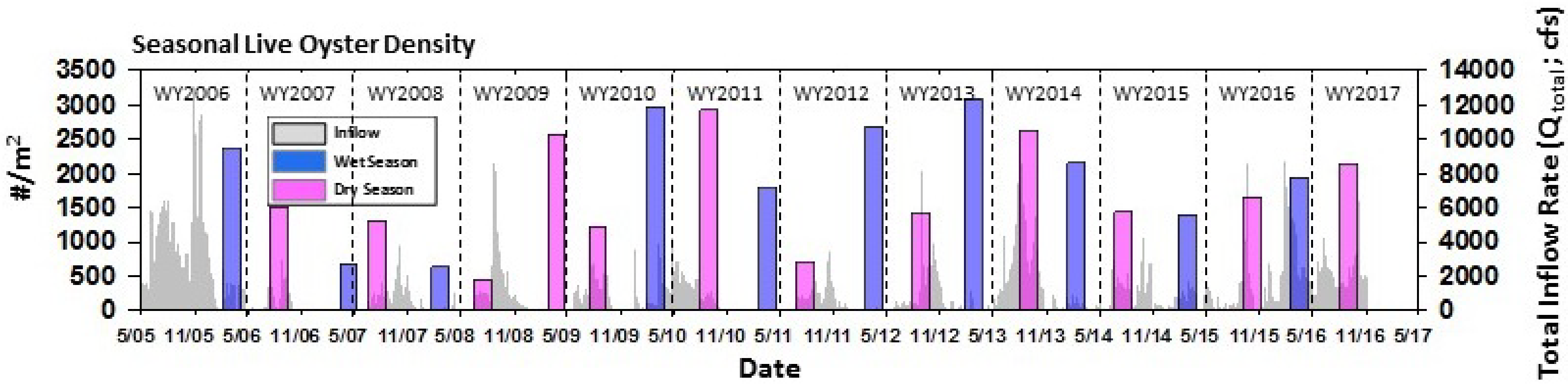


Figure 22. Time series of seasonal live oyster density at Bird Island, near the mouth of the CRE for WY2006–WY2017. (Note: #/m² – number per square meter.)

Water Supply

The CRE MFL Watershed (**Figure 4**) includes a number of existing legal users of water that range across use categories. As described in the *Groundwater and Aquifer Systems* section in **Chapter 3**, the Floridan aquifer system (FAS) is not a primary subject of this discussion since it is not hydraulically connected to surface water in the LWC Planning Area. However, as further use of shallow aquifers and surface water sources have become restricted, the Floridan aquifer has become an important source to meet existing and future demands (**Figure 23**). Throughout the LWC Planning Area, reuse has approximately doubled over the past 20 years to about 80 million gallons per day (MGD).

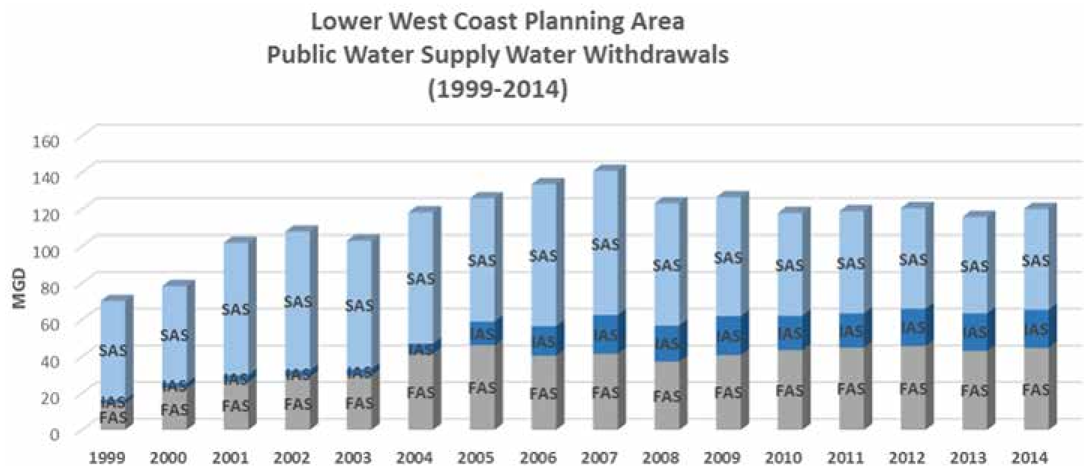


Figure 23. Overall usage of groundwater for public water supply from the various aquifers within the entire LWC Planning Area over time. (Note: FAS = Floridan aquifer system, IAS = intermediate aquifer system, and SAS = surficial aquifer system.[3])

Assessing the risk to the CRE from future increases in consumptive uses includes consideration of existing consumptive use criteria. Two sets of rules restrict the use of groundwater and surface water, respectively.

The maximum developable limit (MDL) rules prohibit groundwater uses from allowing the potentiometric heads within each aquifer to drop less than 20 feet above the top of the uppermost geologic strata that comprises the aquifers at any point during a 1-in-10 drought condition. See the *Lower West Coast Aquifers MFL* section in **Chapter 3**.

The use of surface water within the Lake Okeechobee Service Area is limited to the base condition water use that occurred between April 1, 2001, and January 1, 2008 (Subsection 3.2.1(G) of the *Applicant's Handbook for Water Use Permit Applications within the South Florida Water Management District* [SFWMD 2015]). This restricted allocation area rule prevents increases in surface water use from the basin; eliminating the risk of future surface water use impacting the CRE.

[3] Presented at the 2017 Lower West Coast Water Supply Plan Update Kickoff Meeting in Bonita Springs on June 30, 2017 (www.sfwmd.gov/sites/default/files/documents/lwc_2017_plan_063016_meeting.pdf).

Upstream of S-79, agriculture is the dominant consumptive use relying mostly on surface water to meet supplemental irrigation needs. Public water supply demands are met by a mix of utilities and domestic self-supply. Domestic self-supply includes water used by households served by small utilities (less than 0.1 MGD) and private wells. In Hendry and Glades counties, domestic self-supply meets between one-third and one-half of the population's water demand.

Water supply planning estimates increases in demand across all use categories (public water supply, domestic self-supply, industrial/commercial/institutional, recreational/landscape, power generation, and agricultural) over the next 20 years in this region. However, considering existing criteria on groundwater and surface water, a majority of increased demands are anticipated to be met by a combination of conservation, reclaimed water, and alternative water supplies (SFWMD 2017).

Recreation

Recreational uses of the CRE include swimming, fishing, boating, nature study, and aesthetic pursuits. Recreational uses are affected by high or low freshwater inflows and fluctuating salinity conditions.

Navigation

The C-43 Canal is part of both the C&SF Project and Okeechobee Waterway that connects the Atlantic Ocean to the Gulf of Mexico. It provides navigation through a series of locks that step down the water levels from east to west. S-79 is the westernmost structure.

The portion of the Okeechobee Waterway located west of Lake Okeechobee flows 69.5 miles from Lake Okeechobee to the Gulf of Mexico, supplying fresh water to downstream communities and navigational passage from the lake to the gulf. Water within this system comes principally from measured releases from Lake Okeechobee and watershed runoff, and minimally from groundwater seepage.

Flood Control

As previously stated, the United States Congress passed the Flood Control Act of 1948 authorizing the first phase of the C&SF Project (U.S. Congress 1948). The C-43 Canal, to which the CRE is connected, is an important component of the C&SF Project. The canal conveys water discharged from the East and West Caloosahatchee subwatersheds and water released from Lake Okeechobee when lake levels exceed USACE lake regulation schedules established for flood protection (SFWMD 2014).

The need to provide flood protection as well as navigation within the CRE MFL Watershed requires maintenance of certain minimum and maximum stages within the C-43 Canal. Maximum allowable stage is 3.4 ft National Geodetic Vertical Datum of 1929 (NGVD29) upstream of S-79 and 11.3 ft NGVD29 upstream of S-78. Minimum allowable stage is 2.2 ft NGVD29 upstream of S-79 and 10 ft NGVD29 upstream of S-78. These stages place constraints on the amount of water that can be stored in and released from Lake Okeechobee and the C-43 Canal. At maximum allowable stages, the C-43 Canal contains no appreciable flood storage, so excess runoff must be discharged to tide through S-79 and the CRE.

CHAPTER 5: RESPONSES OF THE CRE TO LOW FRESHWATER INFLOWS IN THE DRY SEASON

BACKGROUND

The S-79 structure marks the head of the CRE, which extends ~26 miles (42 km) downstream to San Carlos Bay (**Figure 24A**). San Carlos Bay is bounded by Pine Island Sound (north) and the Gulf of Mexico (south). The surface area of the MFL waterbody between S-79 and San Carlos Bay (river/estuary) is about 16,715 ac (67.6 km^2). The average depth is 8.9 ft (2.7 m) and approximately 85% of the estuary is less than 6.5 ft (2.0 m) deep (Buzzelli et al. 2013a). The width of the estuary varies from 525 ft (160 m) in the upper narrows near S-79 to ~8,200 ft (2,500 m) at the mouth with the greatest estuarine area from 13.7 to 18.6 miles (~22–30 km) downstream of S-79 (**Figure 24B**; Sun et al. 2016). The narrowest and deepest portion begins at S-79 and continues approximately 7.5 miles (~12 km) downstream (**Figures 24A** through **24C**).

ENVIRONMENTAL PROBLEMS

Many of the ecological problems in the CRE stem from widely fluctuating salinity resulting from high seasonal and interannual variation in discharge that occurs at the Franklin Lock and Dam (S-79). The seasonal and interannual fluctuations in salinity are beyond the tolerances of many organisms within the CRE. These widely fluctuating discharges and salinity levels are a result of the watershed changes, structural alterations, and regulation schedules.

During the wet season, watershed runoff from the basins upstream of the S-79 structure, supplemented by regulatory releases from Lake Okeechobee, reduces salinity levels over most of the estuary. The runoff also darkens the water restricting the depth of light penetration. Large volumes of fresh water can flush most of the salt water from the estuary. Regulatory releases from Lake Okeechobee are required to provide flood protection. These additional discharges from the lake can exacerbate the already low salinity conditions in the estuary and adversely affect marine species (e.g. oysters, seagrasses, etc.).

During dry periods, freshwater inflow can be so low that salt water migrates up to the S-79 structure, truncating the salinity gradient within the estuary. *Vallisneria americana* (tape grass) can become stressed or experience mortality if high salinity conditions persist for too long in the upper estuary. At very low flows, some zooplankters (e.g. mysids, isopods, some fish larvae) become impinged on the S-79 structure and are prevented from moving further upstream (Tolley et al. 2010). These and other species (anchovies, silverside larvae, and smalltoothed sawfish) can become concentrated in the narrow portion of the river just downstream of the structure resulting in habitat compression, increased predation, and competition for limited food resources. Some organisms may be forced to utilize habitat that is physiologically suboptimal, which reduce growth and survival (Petersen 2003).

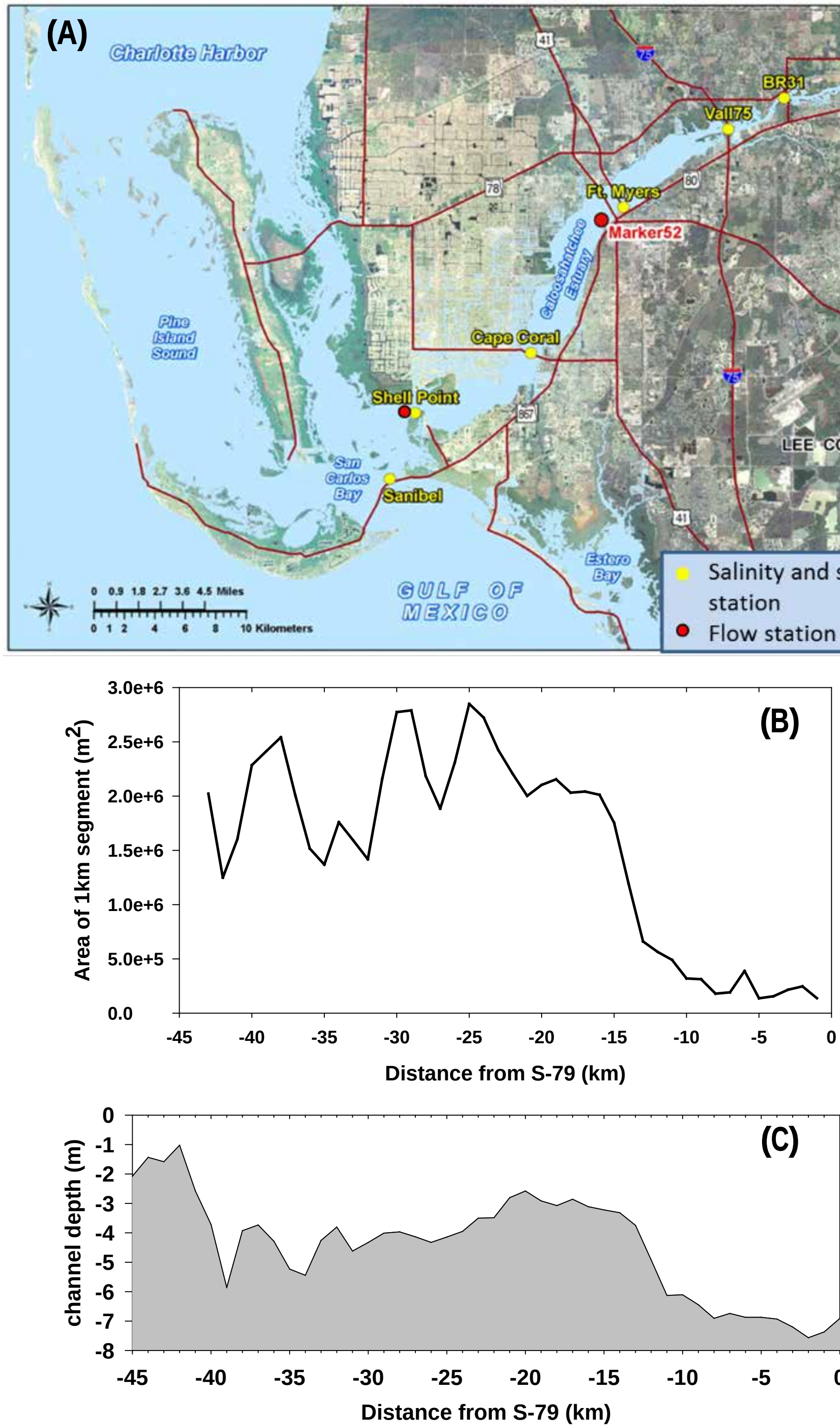


Figure 24. (A) CRE including the Franklin Lock and Dam (S-79) and locations of salinity stations. (B) Area in square meters (m^2) of 1-km segments from S-79 to Shell Point. (C) Longitudinal section depicting change in depth along distance from S-79 at the upstream end (0.0 km).

APPROACH

The current MFL criteria are based on the salinity tolerance of a single habitat forming species, *Vallisneria americana* (tape grass). A primary goal of this reevaluation was to expand the number of indicators and derive criteria that would be more broadly applicable and protective of the estuary as a whole. Organisms ranging in size and complexity from plankton to fish respond to fluctuations in inflow and salinity over a range of time scales. **Appendix A** is a summary of multiple research components conducted to examine inflow-salinity-response patterns among 11 different indicators to evaluate the effects of reduced freshwater inflow on the indicator during the dry season (**Figure 25**). These indicators were selected from a longer list based on overall sensitivity to increased salinity and data availability. The assessment of the potential indicator responses was based on the best available local data and literature information. The different types of data were assembled from a variety of studies of the CRE conducted since the mid-1980s. Thus, the selected "indicators" do not necessarily represent sentinels specifically monitored for the determination of minimum freshwater inflows.

This multi- and interdisciplinary assessment of the relationships between inflow, circulation, salinity, habitats, and biological responses represents the best available scientific knowledge of the CRE. While each study targeted specific concerns regarding the physical and ecological characteristics, together they offer a holistic understanding of the negative effects of diminished freshwater inflow on estuarine ecology. The designation of the magnitudes of minimum inflows to support the various indicators was coupled with a quantitative assessment of the duration of potentially deleterious low freshwater inflows, and, the return frequency of extreme environmental conditions (e.g. drought events).

The approach for determining the CRE MFL depends on incorporating four supporting components: the VEC methodology (USEPA 1988), estimates of the salinity tolerance of estuarine biota, the concept of static and dynamic habitat overlap (Browder and Moore 1981), and a quantitative relationship between salinity and freshwater inflow. The VEC approach applied here focuses on critical estuarine species, communities, and habitats. In many instances, the habitat is biological and typified by one or more prominent species (oysters and seagrasses). In other cases, the habitat may be physical, such as an open water oligohaline zone. Prominent communities are those associated with certain habitats. For example, zooplankton are associated with open water habitat while benthic communities are associated with unvegetated bottom sediments. Maintaining these habitats and communities should lead to a generally healthy and diverse ecosystem. Providing a suitable salinity environment for the habitat-forming species or groups of species should ensure their continued persistence. These salinity requirements form the basis for establishing the CRE MFL.

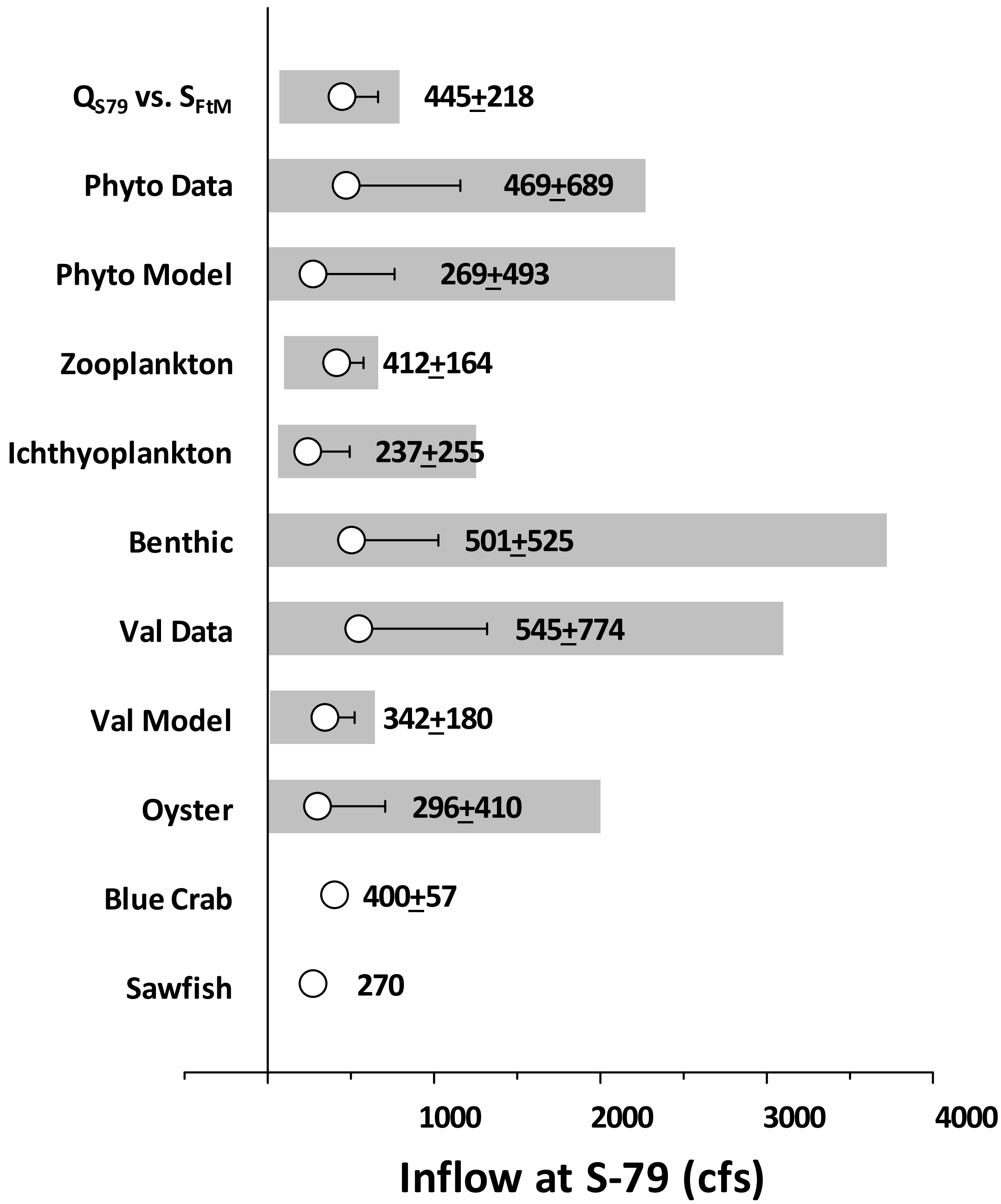


Figure 25. Statistical summary of indicator flows Q_i (cfs) at S-79.
(Notes: See text for methodological details. The range (bar) and average + standard deviation [point + error bar and text] of the estimated indicator inflows for each of the component studies. Q_{S79} – inflow at S-79; S_{FtM} – salinity at Ft. Myers station; Val – *Vallisneria*; and WQ – water quality. An “*” indicates that only one value was estimated for sawfish. An “**” indicates an average from two estimates.)

The concept of static and dynamic habitat overlap (Browder and Moore 1981) is based on the ideas of Gunter (1961) that estuaries serve a nursery function and salinity determines the distribution of species within an estuary, including distribution during different life stages of the same species. The concept also recognizes the importance of the appropriate physical or static habitat to the nursery function and ability of the estuary to support diverse and abundant biotic populations. Freshwater inflow positions favorable salinities relative to important stationary habitat factors such as shoreline, water depth, and bottom type (Browder and Moore 1981). In applying the VEC-habitat overlap approach here, freshwater inflow favorably positioned salinities in areas of the estuary where other environmental requirements of VEC were satisfied. Therefore, estimates of the salinity tolerances, abundance, distribution, and life history of VEC are of critical importance. Tolerances to variation in salinity may be as important as tolerance to different mean salinities. Some of this information was incorporated into a dynamic VEC population model for *Vallisneria* (see Component Study 8 of **Appendix A**), which was used to evaluate the response of this particular VEC to different inflow regimes (also see SFWMD 2000). This *Vallisneria* population model has been updated for this MFL reevaluation.

The last component of the approach is a quantitative relationship between freshwater inflow and salinity. These relationships may come from statistical regressions of salinity (y) on flow (x), hydrodynamic models, or from concomitant measurements of flow and salinity at a particular location in the estuary.

FACTORS AFFECTING CRE SALINITY

The conservative nature of salinity means that, while modulated by physics, it is unaffected by biogeochemical processes. Therefore, estuarine salinity varies spatially over a range of time scales (e.g. hourly to annually) through complex hydrodynamic processes that integrate rainfall, upstream and lateral freshwater inputs, submarine groundwater discharge, wind events, and tidal exchanges (Goodwin 1996, Zheng and Weisberg 2004). The variable influences of these forces affect the relationship between inflow and salinity with distance downstream from S-79. Overall, S-79 inflow accounts for ~60% of the variance in salinity among the monitoring stations (Qiu and Wan 2013). A combination of geomorphology and the circulatory balance between freshwater and oceanic attributes shape estuarine salinity gradients and the time scales for transport and water mass turnover (e.g. flushing or residence time; Sheldon and Alber 2006). The average flushing times for the CRE range from 5 to 60 days with increased time required to replace the estuarine volume as freshwater inflow declines in the dry season (Wan et al. 2013, Buzzelli et al. 2013b). The resulting salinity gradients can be tracked using changes in the positions of target isohalines, or lines of equal salinity, as they move up and down the estuary with fluctuations in freshwater inflow (Jassby et al. 1995, Buzzelli et al. 2014a). Variations in isohaline position and flushing time with variable inflow have implications for both dynamic (water column) and static (benthic) habitats for essential biota.

Inflow Dynamics

Fluctuations in freshwater inflows over time scales ranging from weeks to years have altered salinity regimes and impacted the ecology of the CRE (Chamberlain and Doering 1998; **Appendix A**). Changes in freshwater inflows and salinity affect the distribution and dynamics of many taxa and communities including phytoplankton and zooplankton (Tolley et al. 2010, Radabaugh and Peebles 2012), SAV (Doering et al. 2002, Lauer et al. 2011), oysters and pathogens (La Peyre et al. 2003, Barnes et al. 2007, Volety et al. 2009), fauna inhabiting oyster reefs (Tolley et al. 2006), and fishes (Collins et al. 2008, Heupel and Simpfendorfer 2008, Simpfendorfer et al. 2011, Poulakis et al. 2013, Stevens et al. 2013).

Inflow has been measured at S-79 (Q_{S79}) since 1966 and reported as daily average cfs. Analyses of long-term inflow patterns are contained in Component Study 2 (**Appendix A**). S-79 inflows coinciding with the POR for salinity monitoring (January 1, 2000–January 30, 2016) were included in the present assessment. Q_{S79} approached 15,000 cfs in the wet seasons of 2004 and 2005 before peaking at > 20,000 cfs in September 2006. Between September 2006 and June 2008, the inflow rate was comparatively low (< 1,000 cfs) (**Figure 26A**). Q_{S79} ranged from 0.0 to 16,377 cfs and averaged 1,120 ± 1,760 cfs over 3,021 dry season days, and, ranged from 0.0 to 21,600 cfs and averaged 2,756 ± 3,202 cfs over 2,944 wet season days (**Table 5**). The inflow classes applied by Doering et al. (2006) were used to assess the number and percentage of days where Q_{S79} was within each category (**Table 6**). Q_{S79} was < 500 cfs on almost half (49.0%) of all dry season days on record. The other 41.1% of dry season flow days had inflow rates between 500 and 2,799 cfs. This inflow class was the predominant inflow class in the wet season with ~40% of days in this category.

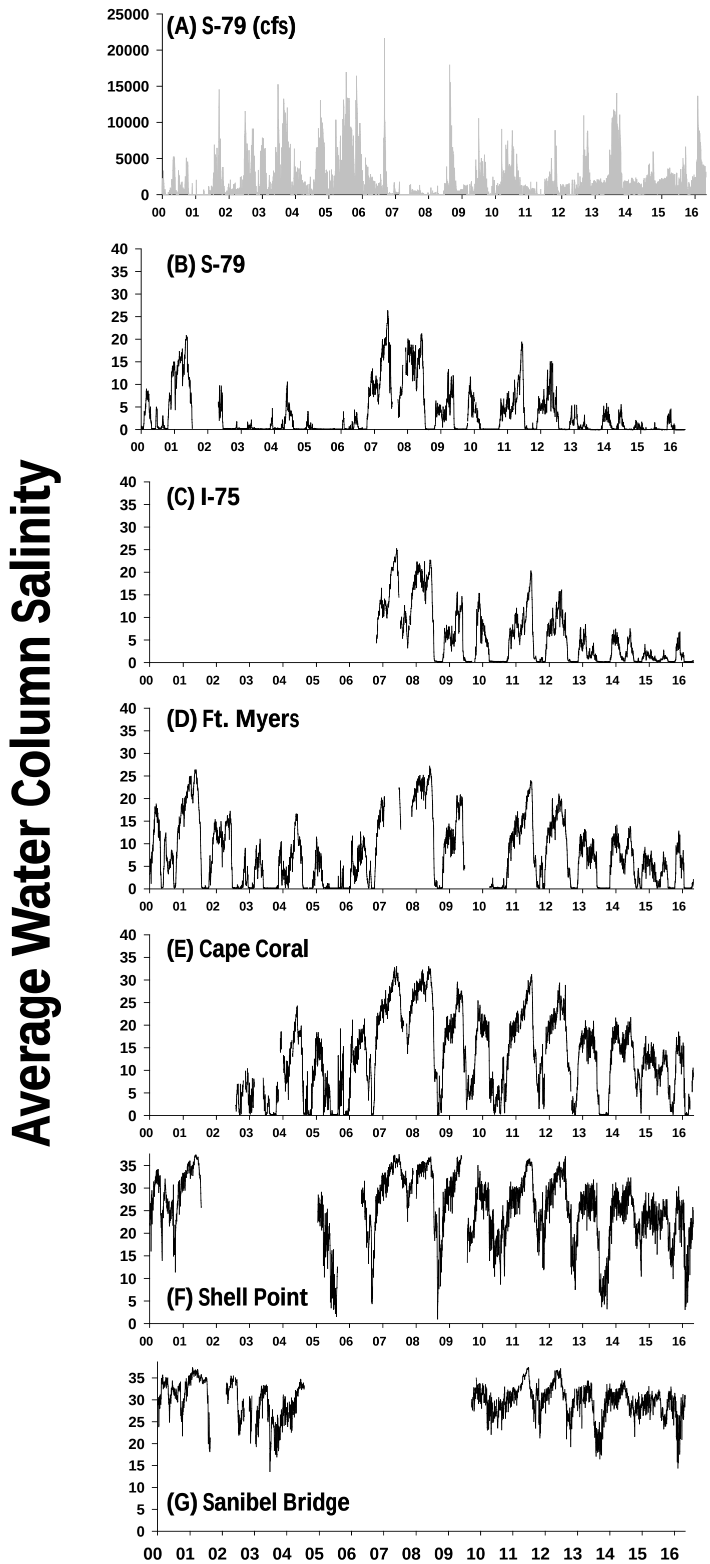


Figure 26. (A) Daily inflow rate from S-79. (B–G) Time series of average daily salinity at S-79, I-75 Bridge, Ft. Myers, Cape Coral, Shell Point, and Sanibel Bridge, respectively.

Table 5. Summary of freshwater inflow through S-79 (Q_{S79}) and salinity at multiple locations in the CRE up to April 30, 2016.

Station	Initial Date	Number of Observations	Inflow or Salinity	
			Range (cfs)	Average ± Standard Deviation (cfs)
Dry Season (November–April)				
Inflow at S-79 (Q_{S79})	1/1/2000	3,021	0.0–16,377	1,120.6 ± 1,760.1 cfs
S-79 (S79)	1/1/2000	2,773	0.1–20.2	4.3 ± 5.1
I-75 Bridge (I75)	11/1/2006	1,811	0.2–22.4	6.9 ± 5.9
Ft. Myers (FtM)	1/1/2000	2,758	0.2–25.1	9.6 ± 6.7
Cape Coral (CC)	11/1/2002	2,352	0.0–32.2	16.0 ± 7.6
Shell Point (SP)	1/1/2000	2,185	3.1–36.9	27.8 ± 5.3
Sanibel Bridge (SAN)	1/1/2000	1,900	14.4–37.4	30.5 ± 3.2
Wet Season (May–October)				
Inflow at S-79 (Q_{S79})	5/1/2000	2,994	0–21,600	2,755.5 ± 3,201.7 cfs
S-79 (S79)	5/1/2000	2,772	0.1–26.4	2.5 ± 4.9
I-75 Bridge (I75)	10/20/2006	1,610	0.1–25.2	4.1 ± 6.3
Ft. Myers (FtM)	5/1/2000	2,624	0.1–27.5	5.3 ± 7.0
Cape Coral (CC)	8/2/2002	2,405	0.1–33.0	10.3 ± 9.1
Shell Point (SP)	5/1/2000	2,132	1.0–37.4	23.0 ± 8.3
Sanibel Bridge (SAN)	5/1/2000	1,795	13.6–37.4	29.1 ± 4.4

Table 6. Summary of daily inflow rates from S-79 for dry (November–April) and wet (May–October) seasons from January 1, 2000, to April 30, 2016.
(Note: Total sample size = 5,966 days.)

Inflow Class	Number in Class (Percentage in Class)	
	Dry (sample size = 3,021 days)	Wet (sample size = 2,944 days)
< 500 cfs	1,480 (49.0%)	794 (27.0%)
500 to 2,799 cfs	1,242 (41.1%)	1,167 (39.6%)
2,800 to 4,499 cfs	139 (4.6%)	341 (11.6%)
≥ 4,500 cfs	161 (5.3%)	642 (21.8%)

Salinity Dynamics

Surface and bottom salinity is monitored at multiple locations (S-79, I-75, Ft. Myers, Cape Coral, Shell Point, and Sanibel). This monitoring started in the 1990s and 2000s. Monitoring at the I-75 station in the upper CRE did not start until 2006 (**Figure 26C**). It should be noted that the sensors at Shell Point and the Sanibel Bridge were out of service from mid-2001 to early 2005, and, from mid-2004 to late 2009, respectively (**Figures 26F** and **26G**). The Shell Point sensor was destroyed by a barge in 2001 and was replaced and relocated to a new location in 2005. The sensor at Sanibel Bridge was damaged by Hurricane Charley in 2004 and was not reconstructed and repaired until 2009. The salinity recorder at Ft. Myers is located centrally in the estuary, has the most comprehensive POR, and provided the foundation and reference for the CRE MFL (**Figure 26D**; SFWMD 2003). Salinity at all stations is reported as average daily values (surface + bottom; **Figure 26**).

Temporally, salinity responds inversely to inflow. The greatest values were observed in 2001, 2007–2008, and 2011 at all monitoring locations (**Figures 26B** through **26G**). There were dry versus wet differences in average salinities (± standard deviation) at all stations including S-79 (4.3 versus 5.1), I-75 Bridge (6.9 versus 4.1), Ft. Myers (9.6 versus 5.3), Cape Coral (16.0 versus 10.3), Shell Point (27.8 versus 23.0), and Sanibel Bridge (30.5 versus 29.1; **Table 5**). Salinity was more variable at the upper CRE stations (S-79, I-75 Bridge, and Ft. Myers) relative to those in the lower estuary (Cape Coral, Shell Point, and Sanibel Bridge).

There were a total of 5,382 daily average salinity values observed at Ft. Myers (dry = 2,758 days and wet = 2,624 days; **Table 7**). Average monthly salinity was greatest in May (11.3 ± 8.6) and least in September (0.9 ± 1.7) (**Table 7** and **Figure 27**). Salinity was more variable during the wet season months; the coefficient of variation (coefficient of variation = [standard deviation/average] x 100) was 111–185% from July to October. The overall distribution of salinity values during these months were non-normal (median < average) with positively skewed outlying data values (**Table 7**). The interquartile range (the middle 50% of the normalized distribution) was greater from March to June due to an overall wider distribution of salinity values at Ft. Myers in these months. The average salinities in the dry and wet seasons were 9.6 ± 6.7 and 5.3 ± 7.0, respectively, again demonstrating the greater variability in the wet season. The negative exponential relationship between average daily salinity and average daily inflow at S-79 was very similar when all the data were used (**Figure 28A**) or just those from the dry season (**Figure 28B**).

Table 7. Salinity statistics for the Ft. Myers monitoring location for January 1, 2000–April 30, 2016, classified by calendar month, dry (November–April) and wet (May–October) seasons, and over all observations (Total).

Period	Sample Size	Range	Average ± Standard Deviation (Coefficient of Variance)	Median	Inter-quartile Range	Skewness
January	487	0.2–24.9	9.9 ± 6.3 (63.6%)	10.4	8.9	0.26
February	425	0.2–25.1	9.6 ± 6.9 (71.2%)	9.2	9.4	0.49
March	471	0.2–25.1	10.0 ± 7.7 (76.6%)	7.9	12.8	0.44
April	479	0.2–24.1	10.2 ± 7.4 (72.6%)	8.7	14.0	0.14
May	466	0.2–27.5	11.3 ± 8.6 (75.7%)	10.7	15.8	0.20
June	443	0.2–26.8	10.0 ± 8.2 (82.3%)	9.5	15.2	0.37
July	450	0.1–21.6	4.6 ± 5.1 (111%)	3.1	6.7	1.16
August	433	0.2–8.6	1.4 ± 2.0 (147%)	0.3	1.3	1.87
September	416	0.1–7.9	0.9 ± 1.7 (185%)	0.2	0.1	2.60
October	416	0.2–12.5	2.9 ± 3.4 (117%)	1.0	4.8	1.07
November	438	0.2–19.9	7.5 ± 5.2 (69.8%)	7.5	8.8	0.18
December	458	0.2–22.2	10.3 ± 5.9 (57.6%)	10.9	8.1	-0.01
Dry	2,758	0.2–25.1	9.6 ± 6.7 (69.6%)	9.2	9.9	0.34
Wet	2,624	0.1–27.5	5.3 ± 7.0 (131%)	1.5	8.0	1.42
Total	5,382	0.1–27.5	7.5 ± 7.2 (95.3%)	6.0	11.9	0.75

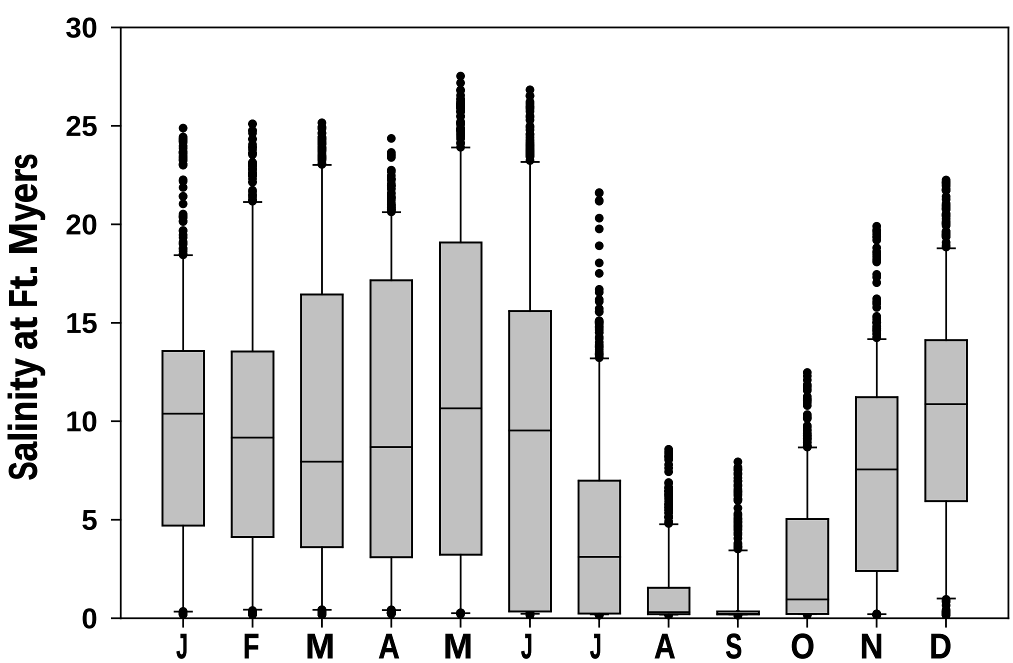


Figure 27. Box plots of salinity values at Ft. Myers by month for January 1, 2000–April 30, 2016. (Notes: The lower and upper edges of the box denote the 25th and 75th percentiles, the horizontal line is the median, and the lower and upper error bars mark the 10th and 90th percentiles.)

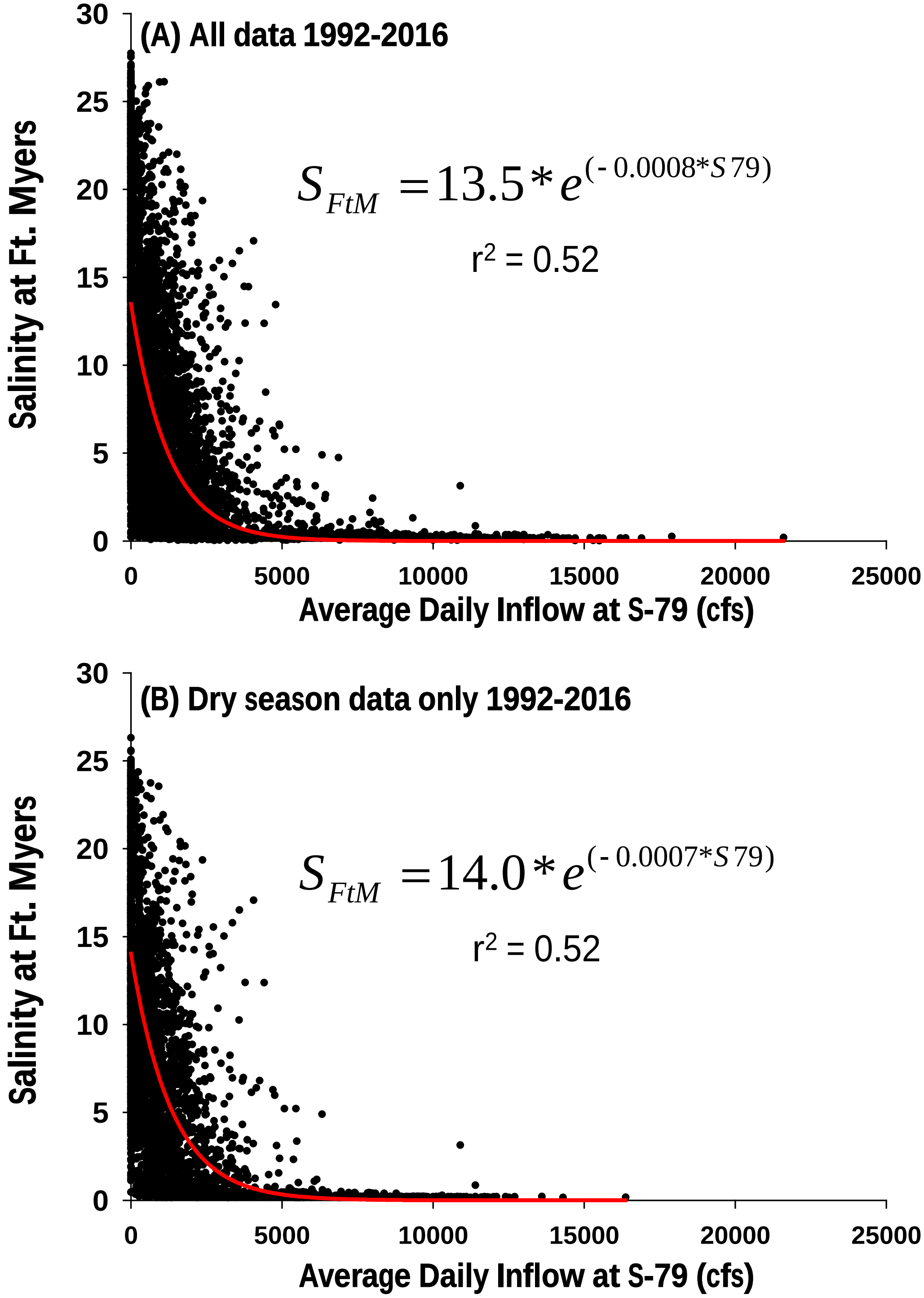


Figure 28. Relationships between average daily inflow at S-79 and average daily salinity at Ft. Myers (S_{FtM}) for (A) all data and (B) dry season data only.

METHODS

Description of Component Studies

This science effort was composed of 11 component studies focused on hydrodynamics, water column and benthic habitats, and faunal indicators (**Table 8**), which are summarized below. While the estimation of estuarine inflow requirements using multiple indicators offers a system of checks and balances, the quantitative assessment of the responses of a particular resource to variable levels of inflow can be very difficult (Adams et al. 2002).

Table 8. List of component studies and the basic description of research methods. (Note: Studies 2 through 11 resulted in estimates of indicator inflow magnitudes.)

	Study	Method
1	Hydrodynamics	Influence of alterations on hydrodynamics
2	Inflow versus Salinity	Monthly freshwater-salinity relationships at Ft. Myers
3	Water Quality	Fine-scale relationships between water quality and inflow
4	Zooplankton	Inflow, zooplankton impingement, and habitat compression
5	Ichthyoplankton	Relationships between ichthyoplankton and inflow
6	Benthic Fauna	Macrofauna-salinity patterns relative to inflow
7	*Vallisneria* Data	Empirical relationships between *Vallisneria*, salinity, and inflow
8	*Vallisneria* Model	Model exploration of *Vallisneria*, salinity, light, and inflow
9	Oyster Habitat	Assess conditions for oyster survival in the lower CRE
10	Blue Crabs	Relationships between blue crab landings, rainfall, and inflow
11	Sawfish	Area and volume of sawfish habitat with variable dry season inflow

RESULTS

Summaries of Component Studies

Component 1: Three-Dimensional Model Evaluation of Physical and Structural Alterations of the CRE: Impact on Salt Transport

Hydrodynamic modeling of estuaries provides a platform to assess the effects of physical alterations on hydrodynamics, transport, and mixing. This study component utilized a three-dimensional hydrodynamic model (Curvilinear Hydrodynamic Three Dimensional Model or CH3D) of the CRE to compare simulated salinities between the existing condition and the reversal of five historical physical alterations to the estuary. The alterations evaluated were the (1) removal of the S-79 structure; (2) removal of the downstream causeway (Sanibel); (3) backfill of the oyster bar near the estuary mouth; (4) backfill of the navigation channel; and (5) the reestablishment of predevelopment bathymetry. Model results indicated that refilling the navigation channel had profound effects with a five-fold reduction in dry season salinity distributions. The reduced salt transport was more pronounced with the predevelopment bathymetry because the estuary was much shallower. Increased estuary depth and cross-sectional area significantly increased salt transport to the upper estuary. Increased salt transport can push biologically relevant isohalines further upstream depending upon freshwater inflow conditions.

Component 2: Analysis of the Relationship between Freshwater Inflow at S-79 and Salinity in the CRE 1993–2013

The upstream migration of salt with reduced freshwater inflow alters the composition and productivity of oligohaline habitats in estuaries. This process can be problematic in subtropical estuaries with regulated freshwater inflow. This study component examined the relationships between average monthly inflow and mid-estuary salinity from 1993 to 2013. An exponential decay equation was fit to the inflow-salinity relationship for each water year (May 1 to April 30). Annual equations were used to estimate the inflow rate associated with a salinity of 10 at the Ft. Myers monitoring station. Inflows varied intra- and interannually. The inflow rate ranged from 70 to 773 cfs with an average of 445 ± 218 cfs. At the estuary and annual scales, the quantity of fresh water needed to support a particular salinity target varied greatly. This variance was related to the changes in freshwater inputs from the C-43 Watershed and Tidal Caloosahatchee Subwatershed.

Component 3: Relationships between Freshwater Inflows and Water Quality Attributes during the Dry Season in the CRE

Decreased flushing with reduced inflow can lead to the deposition of phytoplankton biomass and bottom water hypoxia in estuaries. This study component utilized event-scale water quality data, long-term monitoring of chlorophyll *a*, and simulation modeling of phytoplankton dynamics to evaluate low freshwater inflows that could contribute to water quality problems in the upper CRE. The highest chlorophyll *a* and lowest dissolved oxygen concentrations occur in the upper CRE under low inflows. Although more research is needed, it is hypothesized that dry season inflows of less than approximately 500 to 600 cfs may promote bottom water hypoxia in the deeper channel of the upper CRE. Field and model results indicated that chlorophyll *a* concentrations greater than the water quality standard of 11 micrograms per liter were associated with inflows of 469 ± 689 cfs and 269 ± 493 cfs, respectively. Low level inflows (< 500 cfs) need to be further studied to better quantify the discharge required to mitigate the potential for hypoxia in the upper CRE.

Component 4: Zooplankton Response to Freshwater Inflow in the CRE

Freshwater inflow to some estuaries, including the CRE, is regulated through control structures. Zooplankton assemblages provide an essential food web link whose position in the estuary fluctuates with inflow. Unfortunately, zooplankton habitat can be impinged and compressed due to the presence of a water control structure as inflow is reduced in the dry season. This study assessed impingement and habitat compression for CRE zooplankton under reduced inflow. Data were used from a CRE study conducted by Florida Gulf Coast University from 2008 to 2010. Zooplankton samples were collected monthly at each sampling site at night during a flood tide. The centers of abundance for the 13 taxa investigated migrated downstream and upstream as freshwater inflow increased and decreased, respectively. Both habitat compression and impingement were potentially harmful for zooplankton assemblages in the estuary. Impingement was possible if inflow from the S-79 structure ranged from 98–566 cfs and averaged 412 ± 165 cfs. Almost all taxa investigated (except *Menidia*) experienced habitat compression if the centers of abundance was < 12 km downstream of S-79.

Component 5: Ichthyoplankton Response to Freshwater Inflow in the CRE

Ichthyoplankton communities are key components of food webs in the upper, oligohaline reaches of most estuaries. This study analyzed historical (1986–1989) data to evaluate effects of salinity and freshwater inflow on ichthyoplankton communities in the CRE. Abundance of ichthyoplankton was greatest when the 30-day inflows at S-79 averaged between 151 and 600 cfs. Juvenile fish appeared to prefer salinities < 10 and their abundance was centered near Beautiful Island. Flows at S-79 associated with a salinity of 10 near Beautiful Island averaged 237.5 ± 255.5 cfs. Flows less than this could result in loss of favorable habitat.

Component 6: Summary and Interpretation of Macrobenthic Community Properties Relative to Salinity and Inflow in the CRE

The composition, distribution, and density of benthic invertebrate communities (macrofauna) can be used as indicators of salinity and inflow for estuaries. The goal of this study component was to explore the relationships between inflow, salinity, and benthic macrofauna in the CRE. Benthic samples were collected every 2 to 4 months at seven stations during two periods (February 1986–April 1989 and October 1994–December 1995). The abundance, diversity, and composition of the macrofaunal community were determined relative to observed fluctuations in salinity. Four distinct zones emerged based on salinity ranges and the composition of the macrobenthic community. Conditions conducive to maintain the characteristic community observed during the sampling periods in the most upstream zone (salinity = 0 to 4, 0 to 7 km from S-79) occurred on 54% of dry season days from 1993 to 2012. The indicator inflows ranged from 0 to 3,720 cfs and averaged 501 ± 525 cfs for the days where salinity was 3 to 4 (sample size was 181).

Component 7: Relationships between Salinity and the Survival of **Vallisneria americana** *in the CRE*

Vallisneria americana is sensitive to increased salinity in many estuaries, including the CRE. Much of the *Vallisneria* observed from 1993 to 1999 in the CRE has been lost since droughts in 2001 and 2007–2008. This study examined relationships between *Vallisneria* and salinity through change-point analysis, assessment of long-term patterns of abundance, and exploration of the effects of salinity exposure time. Change-point analysis revealed salinity thresholds of 4, 9, and 15. Dry season average daily salinity was ~5 and rarely exceeded 10 when *Vallisneria* was abundant from 1993 to 1999. Indicator inflows ranging from 0 to 3,160 cfs and averaging 545 ± 774 cfs were associated with dry season salinity values of 9 to 10 at Ft. Myers from 1993 to 1999 (sample size was 63). In contrast, *Vallisneria* was virtually absent from 2007 to 2013 as dry season average daily salinity exceeded 10. Negative changes in shoot density can be rapid as ~50 to 60% of the aboveground material can be lost if salinity was > 10 for 2 to 3 weeks. These results highlight the effects of both the magnitude and duration of environmental conditions that can inhibit *Vallisneria* survival in the CRE.

Component 8: Development and Application of a Simulation Model for **Vallisneria americana** *in the CRE*

Monitoring of *Vallisneria* densities in the upper CRE from 1998 to 2007 was accompanied by mesocosm experiments to determine relationships between salinity and growth. This study built upon these efforts by developing a simulation model to examine the effects of temperature, salinity, and light on *Vallisneria* survival and biomass in the upper CRE from 1998 to 2014. The effects of salinity on *Vallisneria* mortality were explored using an 8-year experimental model based on favorable conditions from 1998 to 1999. Using the experimental model, the dry season salinity was systematically increased in 5% increments until the net annual biomass accumulation of *Vallisneria* was negative. A five-fold increase in grazing was required to stabilize model biomass under optimal conditions. A 55% salinity increase to 12 promoted shoot mortality in the experimental model. Annual inflow-salinity relationships for Ft. Myers were used to estimate that dry season inflows ranging from 15.2 to 629.0 cfs and averaging 342 ± 180 cfs were associated with a salinity of 12 at Ft. Myers. Model results suggested that an estimated 85.4 and 86.7% of the shoots were lost in the dry seasons of 2001 and 2007, respectively.

Component 9: Assessment of Dry Season Salinity and Freshwater Inflow Relevant for Oyster Habitat in the CRE

Short- and long-term alterations of salinity distributions in estuaries with variable freshwater inflow affects the survival, abundance, and extent of oyster habitat. The objective of this study was to evaluate salinity conditions at Cape Coral and Shell Point in the CRE. Salinity data from the 2006–2014 dry seasons (November–April) were categorized relative to oyster habitat criteria and related to freshwater inflow. Daily salinity was within the appropriate range for oysters (10–25) on 70.1% of the observations. Daily inflow ranged from 0 to 2,000 cfs and averaged 296 ± 410 cfs when salinity ranged from 20 to 25 at Cape Coral in the dry season. The influence of the marine parasite *Perkinsus marinus* (dermo) is limited due to the subtropical climate where temperature is low when salinity is high (dry season) and temperature is high when salinity is low (wet season). Overall salinity patterns were favorable for oyster survival at the upstream extent of oyster habitat in the CRE.

Component 10: Ecohydrological Controls on Blue Crab Landings and Minimum Freshwater Inflow to the CRE

A 28-year POR was used for blue crab landings in the CRE was used to establish relationships between (1) changes in hydrology and water resource function and (2) the magnitude of the functional loss and time to recover. Annual catch per unit effort (CPUE), computed from monthly landings of crabs and measures of fishing effort, represented the resource function. Annual landings expressed as unadjusted and de-trended CPUE were found to be significantly correlated with hydrologic variables, rainfall, and freshwater inflow during the previous year's dry season. Increases in CPUE from one year to the next were also positively related to dry season rainfall in the first of the two years. Geometric mean functional regressions and Monte Carlo simulations were used to identify the dry season rainfall associated with losses of water resource function that required 1, 2, or 3 years of average dry season rainfall to recover. A spectral analysis indicated that time series of both dry season rainfall and blue crab catch had periodicities of 5.6 years. A Monte Carlo analysis revealed that the rainfall associated with two- and three-year recoveries had return intervals of 5.8 and 8.2 years, respectively.

Component 11: Relationships between Freshwater Inflow, Salinity, and Potential Habitat for Sawfish (Pristis pectinata) in the CRE

The smalltooth sawfish (*Pristis pectinata*) is an endangered species that historically ranged from Texas to North Carolina. The distribution and abundance of sawfish have declined due to overfishing and habitat loss. Presently, the CRE is an important sawfish nursery. Juvenile sawfish habitat can be characterized as nearshore environments < 1 m in depth, where salinities range from 12 to 27. This study quantified sawfish habitat with variable inflow to the CRE in the dry season using a combination of bathymetric analyses and hydrodynamic modeling. Inflows of 150–300 cfs positioned the 12 and 27 salinities in the shallowest part of the estuary (10 to 30 km downstream). Specifically, the area of sawfish habitat was greatest (5.7 km^2) when inflow through the S-79 structure was 270 cfs in the dry season. Under reduced inflow, the habitat migrated into the channel above Beautiful Island where it was compressed against S-79. Higher inflows pushed the location of salinity 27 out of the estuary.

SUMMARY

This chapter focused on the science completed for the CRE to provide a strong science foundation to support the MFL reevaluation. This updated science documentation explored new data since the adoption of the existing MFL criteria in 2001 (SFWMD 2000) and the 2003 MFL update (SFWMD 2003), analyzed older data, and used updated statistical approaches and modeling. The previous science approach in 2001 and 2003 was criticized for being focused on the salinity tolerance of a single species, *Vallisneria americana*, which the existing MFL criteria are based upon. This updated science documentation utilized a VEC approach by examining multiple indicator species (e.g. aquatic vegetation, oysters, benthic communities, blue crabs, etc.) within the entire spatial extent of the estuary where the MFL waterbody is located (between S-79 and San Carlos Bay). This suite of different ecological indicators was used to assess the minimum S-79 inflows that support the various indicators and in many cases revealed when a negative change occurred. This effort was composed of 11 component studies focused on hydrodynamics, water column and benthic habitats, and faunal indicators. These component studies targeted specific concerns regarding the physical and ecological characteristics, together they offer a holistic understanding of the negative effects of diminished freshwater inflow on estuarine ecology. Additional technical details about the specifics of each component study are contained in **Appendix A**.

CHAPTER 6: METHOD AND RATIONALE TO DEFINE THE MINIMUM FLOW CRITERIA

SIGNIFICANT HARM

A minimum flow or minimum water level is the limit at which further withdrawals cause significant harm to the water resources or ecology of the area (Section 373.042(1)(a), F.S.. Significant harm is the temporary loss of water resource functions, which result from a change in surface water or groundwater hydrology, that requires more than two years to recover, but which is considered less severe than serious harm. Serious harm means the long-term loss of water resource functions resulting from a change in surface or groundwater hydrology (Rule 40E-8.021, F.A.C.).

Minimum flow or minimum water level criteria contain three different elements: a magnitude, a duration, and a return frequency. The **magnitude** is the flow (in cfs or other units as appropriate) or water level (stage) below which significant harm occurs. The **duration** is the length of time that the flow or level can be below the minimum before significant harm occurs. The **return frequency** concept recognizes that flows and levels associated with significant harm will occur naturally due to climatic fluctuations. The return frequency is the number of times, in a given period of time, that minimum flows or minimum water levels can be expected to occur naturally. An exceedance occurs when the MFL falls below a certain flow (magnitude) for a duration greater than specified for the waterbody. A violation occurs when MFL falls below the magnitude (minimum threshold) for a duration and frequency greater than specified for the waterbody. When significant harm does occur, the water resource functions are expected to take more than two years to recover. This chapter is organized in terms of the **magnitude, duration, and return frequency**.

The minimum flow will be expressed as a mean monthly flow measured at the Franklin Lock and Dam (S-79). The Franklin Lock and Dam was chosen as the compliance site for (1) its location at the head of the estuary, (2) nearly 80% of the total long-term freshwater inflow to the estuary occurs at S-79, (3) freshwater inflow is routinely measured at S-79, and (4) discharge from the C-43 Reservoir, now under construction, will supplement flows at S-79 to help achieve the MFL. The monthly time scale for flow averaging was chosen for both technical and practical reasons. A thirty-day averaging period commonly yielded significant relationships between inflow, salinity patterns, and estuarine indicators (**Appendix A**).

From a practical perspective, managing flows on shorter time scales could limit flexibility and might conflict with other environmental goals. Managed discharges at S-79 are seldom delivered as a steady flow, particularly at low levels. Rather, low level managed flows at S-79 are delivered as a pulse, mimicking a rainfall event. Daily deliveries vary, building to a peak in the first few days and tailing off, often to 0 cfs after that. Pulses are shown to prevent stratification and may discourage algal blooms and low dissolved oxygen concentrations through vertical mixing. A minimum flow would likely be delivered as a pulse, designed to attain a 7- or 10-day average equal to the minimum flow. However, inflows to the estuary on any given day may be higher or lower than the minimum.

RESOURCE-BASED APPROACH

SFWMD uses a resource-based approach to determine minimum freshwater inflow requirements in coastal systems throughout South Florida (Hunt et al. 2005, SFWMD 2000, SFWMD 2002a, 2002b, 2003, 2006b). The approach combines the VEC approach (USEPA 1988) and the habitat overlap concept of Browder and Moore (1981).

The VEC approach was developed by the United States Environmental Protection Agency as part of its National Estuary Program (USEPA 1988). A VEC can be any part of the environment that is considered important. As applied to coastal systems, the approach focuses on critical estuarine habitat, communities, and species. In many instances, that habitat is biological and typified by one or more prominent species such as *Vallisneria* or oysters. However, the habitat may be physical, such as open water, lateral shoals, or upstream oligohaline zones. Critical estuarine communities may include zooplankton (including ichthyoplankton) or benthic infauna. Critical species may include those that support commercial fisheries (e.g. blue crab) or are endangered (e.g. smalltoothed sawfish). VECs serve as indicators of a healthy estuarine system, and their freshwater inflow requirements are used to establish minimum flows.

The concept of static and dynamic habitat overlap (Browder and Moore 1981) is based on the ideas of Gunter (1961) that (a) estuaries serve a nursery function and (b) salinity determines the distribution of species and/or different life stages of a species within an estuary. The concept also recognizes the importance of appropriate physical or static habitat to the nursery function and ability of the estuary to support diverse and abundant faunal populations. Freshwater inflow positions favorable salinities relative to important stationary habitat factors such as shoreline, water depth, and bottom type (Browder and Moore 1981). Because different organisms occupy different positions along the estuarine salinity gradient (e.g. Bulger et al. 1993), changes to the salinity gradient, such as compression or truncation resulting from structural alterations, may impact nursery function and result in reduction in diversity and abundance of fish and wildlife.

In most cases, freshwater inflows required by a VEC are determined by (1) identifying important resources and their location in an estuarine system (e.g. oysters, SAV, and shallow water habitat); (2) determining the salinity tolerances of these resources; (3) determining the relationship between freshwater inflow and the distribution of salinity within the estuary; and (4) determining the freshwater discharge that produces overlap between a resource and its tolerable salinity. The responses of estuarine biota to freshwater inflow are not always mediated through their salinity tolerance but may be directly due to flow. The longitudinal position of planktonic organisms within an estuary can vary directly with freshwater inflow (Peebles and Greenwood 2009) in response to changes in transport.

It is important to note that this approach does not rely on an historical record of natural freshwater inflows to derive a minimum flow. Rather, this approach recognizes that the temporal and spatial distribution of freshwater inflows to coastal systems in South Florida have been highly altered from their historical state (**Chapter 2**). The recommended MFL criteria are based on existing estuarine resources with the existing changes and structural alterations that have occurred to the watershed.

The *Assessment of the Responses of the Caloosahatchee River Estuary to Low Freshwater Inflow in the Dry Season* document is composed of 11 component studies to reevaluate the MFL for the CRE (**Appendix A**). The resource-based approach was applied to estimate the freshwater inflows that might be ecologically unsuitable in the dry season. The component studies emphasized the relationships between the indicators or VECs and inflows through the S-79 structure. The "indicator inflow" or Q_I was defined as the S-79 inflow threshold below which there would be negative impacts, but not necessarily significant harm. There were 11 different approaches to estimate Q_I (Study Components 2 through 11, **Table 9**). Component 1 did not result in estimates of Q_I (Sun et al. 2016). Component Studies 2 (inflow versus salinity), 3 (monitoring and modeling of water quality), 5 (ichthyoplankton), 6 (benthic macrofaunal), 7 (*Vallisneria* data), 9 (oyster habitat), and 11 (sawfish) related suitable salinity conditions to inflow at S-79. Q_I values derived from Component Studies 4 (zooplankton) and 10 (blue crab) were determined by linking the estuarine resource directly to inflow and/or precipitation. Finally, the *Vallisneria* simulation model (Component 8) was used to connect the estuarine indicator to salinity patterns and freshwater inflow. Component Study 1 evaluated the potential effects of watershed alterations on the CRE (Sun et al. 2016). Component Studies 2 through 11 each resulted in estimates of indicator inflow magnitudes.

Table 9. List of component studies and the basic description of research methods from the *Assessment of the Responses of the Caloosahatchee River Estuary to Low Freshwater Inflow in the Dry Season* document (**Appendix A**).

	Study	Method
1	Hydrodynamics	Influence of alterations on hydrodynamics
2	Inflow versus Salinity	Monthly freshwater-salinity relationships; inflow required to produce salinity = 10 at Ft. Myers salinity station
3	Water Quality	Fine-scale relationships between water quality and inflow
4	Zooplankton	Inflow, zooplankton impingement, and habitat compression
5	Ichthyoplankton	Relationships between ichthyoplankton and inflow
6	Benthic Fauna	Macrofauna-salinity patterns relative to inflow
7	*Vallisneria* Data	Empirical relationships between *Vallisneria*, salinity, and inflow
8	*Vallisneria* Model	Model exploration of *Vallisneria*, salinity, light, and inflow
9	Oyster Habitat	Flow-salinity and oyster survival in the lower CRE
10	Blue Crabs	Relationships between blue crab landings, rainfall, and inflow
11	Sawfish	Area and volume of sawfish habitat with variable dry season inflow

A summary of the magnitude findings of the component studies is as follows:

- **Component Study 1** utilized hydrodynamic modeling as a tool to explore changes in circulation and salinity caused by structural alterations at the estuary scale. It did not provide estimates of inflows relative to estuarine response variables.
- **Component Study 2** used the relationship between average monthly inflow at S-79 and average monthly salinity at the Ft. Myers salinity station to estimate the quantity of fresh water associated with a salinity value of 10 from WY1993 to WY2013.
- **Component Study 3** emphasized the relationship between low inflow and elevated chlorophyll *a* concentrations to estimate Q_I when chlorophyll *a*

concentrations in the upper CRE was greater than the impaired estuarine waters target of 11 micrograms per liter (µg L^{-1}) (FDEP 2009). This approach was applied independently to both empirical and model-derived chlorophyll *a* concentration values.

- **Component Study 4** estimated Q_I as the inflow threshold below which the upstream movement of the zooplankton community would be impinged against the S-79 structure.
- **Component Study 5** utilized salinity preference of ichthyoplankton (juvenile fish) to estimate the habitat area with reduced inflow.
- **Component Study 6** estimated Q_I from inflows on the days when the salinity in the upper CRE was greater than the tolerance range associated with the characteristic benthic macrofauna community.
- **Component Study 7** extracted dry season days where the salinity at the Ft. Myers station ranged from 9 to 10 from WY1993 to WY1999 when *Vallisneria* was abundant to calculate Q_I.
- **Component Study 8** applied a *Vallisneria* simulation model to identify the salinity and inflows where *Vallisneria* experienced net mortality.
- **Component Study 9** estimated Q_I by averaging flows from days where the salinity at Cape Coral was 20 to 25 from WY2005 to WY2014 concurrent with oyster monitoring.
- **Component Study 10** examined the relationships between rainfall and Lee County blue crab catch data. Q_I was estimated from rainfall-discharge relationships.
- **Component Study 11** assessed the impact of inflows on the area of favorable habitat for the endangered sawfish in the dry season.

As stated above, a minimum flow has three attributes: a magnitude, a duration, and a return frequency. Each individual component did not always provide estimates of all three. While 10 of the studies allowed estimates of a magnitude of flow, only one study explicitly provided estimates for return frequency (blue crab) and none explicitly arrived at an estimate of duration. The remainder of the chapter describes how the three attributes of a minimum flow were estimated. The magnitude was derived from results of the 10 components that provided estimates of Q_I. Duration was estimated using the Tape Grass Model. Finally, the return frequency was determined from results of the blue crab study (Component 10) and further analyses of historical rainfall time series was used.

Magnitude

The analyses of indicators resulted in 10 separate means and standard deviations (SDs) for Q_I (**Figure 29**). First, the grand mean of Q_I was calculated using the 10 independent mean values. Second, the median value of Q_I was calculated from the ten mean values. However, each independent analysis was from a different data source with different sample sizes, and in some cases, a different analytical approach. Thus, the third alternative utilized a composite normal probability density function (NPDF) derived from individual NPDFs, each with respective means and SDs (**Equation 1**).

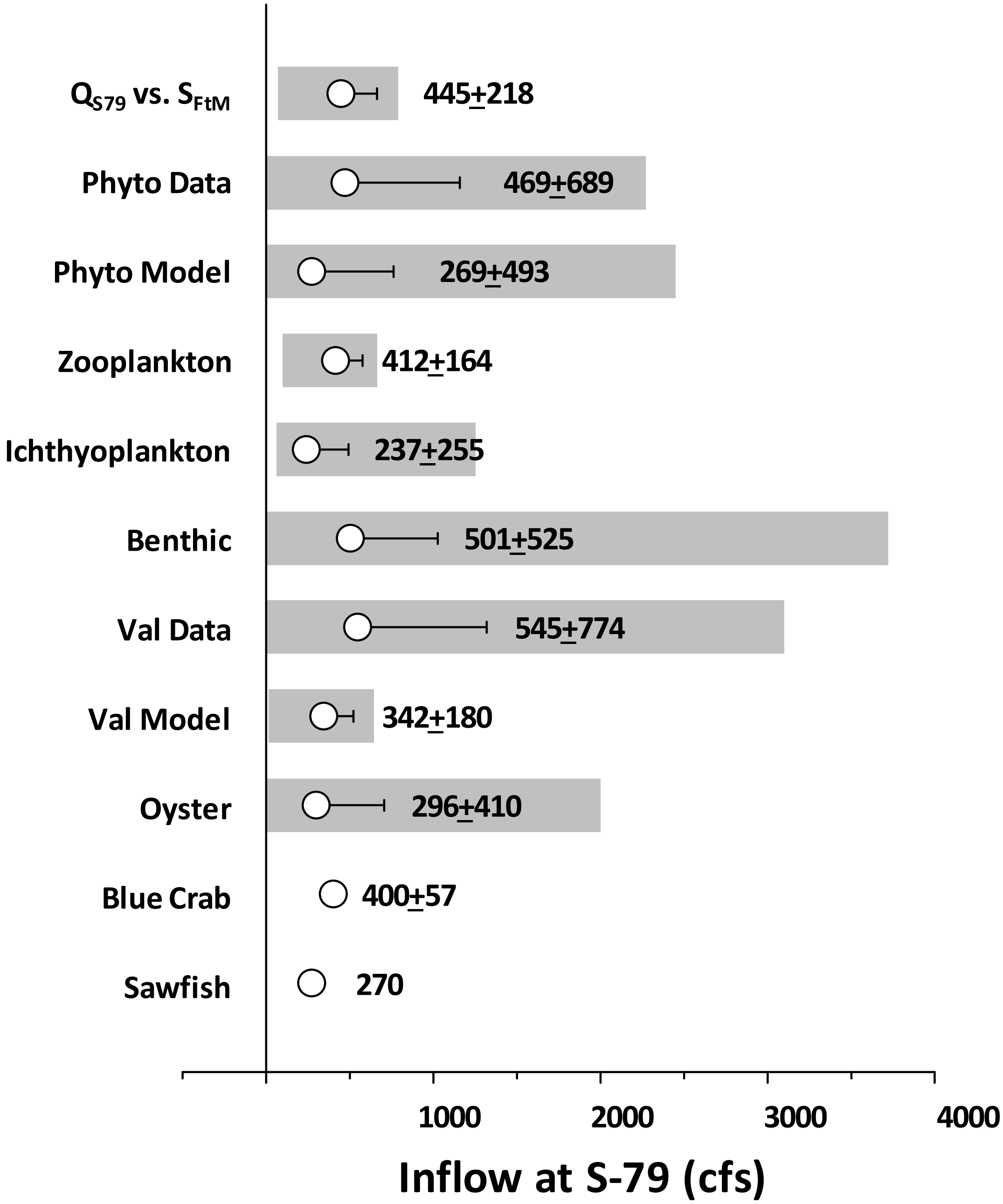


Figure 29. Statistical summary of indicator flows Q_i at the S-79 structure. (Notes: See text for methodological details. The range (bar) and average + SD [point + error bar and text] of the estimated indicator inflows for each of the component studies. Q_{S79} – inflow at S-79; S_{FtM} – salinity at Ft. Myers station; Val – *Vallisneria*; and WQ – water quality.)

$$y = \left(\frac{1}{\sigma\sqrt{2\pi}}\right) * e^{\frac{-(x-\mu)^2}{2\sigma^2}} \qquad (1)$$

Where:

μ = mean inflow rate (cfs)

σ = standard deviation of inflow rate (cfs)

x = ln transformed (x+1) freshwater inflow rate at S-79 (cfs)

The NPDF resulted in a predictive function (F(x) = y) for each indicator over the range of possible dry season inflow rates. Nine sets of mean ± SD were incorporated from various ecological indicators. The sawfish indicator (Component Study 11) was omitted because it did not have a SD. The oyster habitat indicator (Component Study 9) was better suited to higher, wet season inflow rates.

The raw inflow rates were natural log-normal transformed (y = ln(x+1)). The nine predicted "y" values for each discrete "x" value were averaged to derive a composite NPDF over all indicators (**Figure 30**). The red line is the average of all density functions. The ln-transformed mean x (μ) ± SD from the composite NPDF was 5.9 ± 0.66, with the ± 1 SD range being 5.24 to 6.56. Detransformation results in a mean of 365 cfs and a ± 1 SD range of 188 to 706 cfs. The mean from the NPDF composite compares favorably with the estimates from the grand mean (381 cfs) and median (400 cfs) values over all ten estimates of Q_I. Given the respective error among each estimate (+ 1 SD for grand mean and interquartile range for the median, **Table 10**), they are indistinguishable from each other and result in equivalent salinity conditions in the upper CRE. Based on the regression between inflow at S-79 (Q_{S79}) and salinity at Ft. Myers (S_{FtM}) derived in Component 2 of **Appendix A**, S_{FtM} would range 11.4 (365 cfs), 11.2 (381 cfs), and 11.0 (400 cfs), respectively.

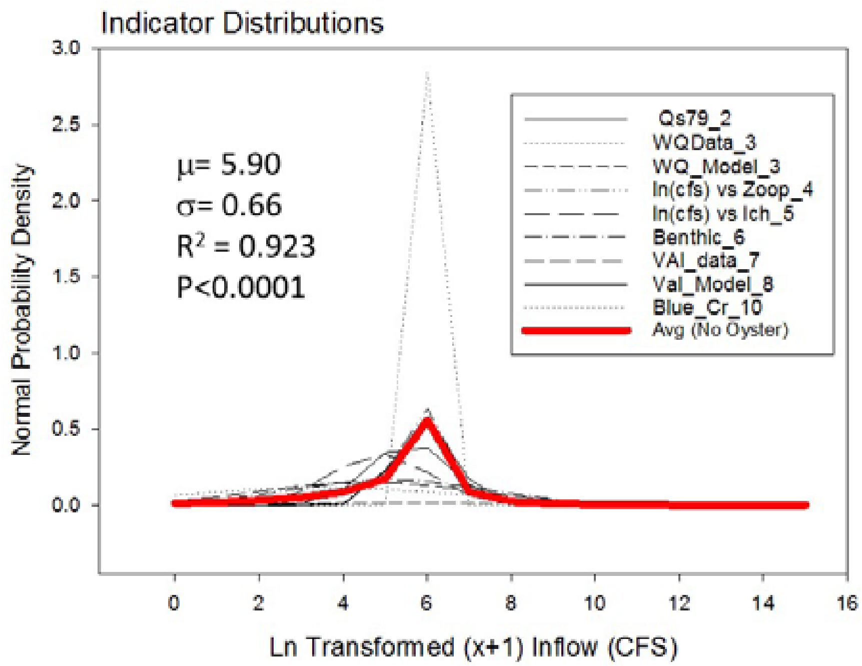


Figure 30. Normal probability function calculated for each indicator. (Notes: Numbers refer to component number in the *Assessment of the Responses of the Caloosahatchee River Estuary to Low Freshwater Inflow in the Dry Season* document [**Appendix A**]. The bold red line is the average of all density functions.)

Table 10. Summary of estimates of the magnitude of the minimum flow at S-79.

Method	Flow (cfs)	SD (cfs)	± 1 SD (cfs)
Indicator Means	381	104	277–485
Indicator Median	400		283–457 [a]
Normal Density [b]	365		188–706

a. Based on the interquartile range.
b. Calculated from mean and standard deviation of lognormal estimates given in **Figure 30**. Oysters are excluded but the mean changed only slightly if they were included (361 cfs).

DURATION

Vallisneria americana (American tape grass) offers a particularly useful indicator of environmental conditions in the CRE. It supports essential estuarine goods and services, is sensitive to salinity fluctuations at the ecosystem scale, and has value to a variety of stakeholders (Dale and Beyeler 2001). The location of the *Vallisneria* habitat in the upper estuary and its negative response to increased salinity makes it an excellent candidate as an ecological indicator for freshwater inflow (Chamberlain and Doering 1998, Doering et al. 2002). A combination of monitoring, mesocosm, and modeling results allow the application of tape grass responses as a platform to quantify the effects of high salinity duration in the upper CRE.

Vallisneria is a freshwater SAV commonly found in lakes, rivers, and oligohaline reaches of estuaries (Bortone and Turpin 2000, McFarland 2006). *Vallisneria* habitat supports a variety of ecologically and commercially important fauna (Hauxwell et al. 2004, Rozas and Minello 2006).

Since it is a freshwater macrophyte, *Vallisneria* is sensitive to salinity intrusion into the upper areas of estuaries including the CRE (Doering et al. 2002, Boustany et al. 2010). While salinity $\geq$ 10.0 is detrimental, water clarity can be a complicating factor that affects to *Vallisneria* survival and growth. This is because submarine light penetration in the upper part of estuaries, such as the CRE, is often influenced by colored dissolved organic matter contained in freshwater inflow (McPherson and Miller 1987, Bowers and Brett 2008, Buzzelli et al. 2014b, Chen et al. 2015). The significance of colored dissolved organic matter for *Vallisneria* survival is that the low salinity conditions necessary to maintain tape grass are often coupled to reduced water clarity.

Component Study 8 (**Appendix A**) reviewed the development and initial application of a simulation model for *Vallisneria* in the CRE. The model was designed to represent changes in shoot biomass at Site 1 over an 18-year period from 1997 to 2014. The input data and model results from 1998 to 2014 (6,209 days) were analyzed. Water temperature, submarine irradiance, and salinity were the primary environmental drivers in the *Vallisneria* model. A daily time series of water temperature at Ft. Myers from 1997 to 2014 was derived from continuous monitoring. Daily salinity at Site 1 was predicted using a three-dimensional hydrodynamic model (Sun et al. 2016). The rates of gross production and mortality decreased and increased, respectively, as salinity increased from 0 to 10 (Doering et al. 2002). Therefore, while salinity $\geq$ 10 shut down gross production, the mortality rate was maximized.

Surface light was attenuated by water depth and the total attenuation coefficient to derive irradiance at the bottom. The total attenuation coefficient contained contributions from pure water, color, turbidity, and chlorophyll *a* (McPherson and Miller 1987). The equations for *Vallisneria* were similar to those used in modeling of seagrasses (*Syringodium filiforme*, *Halodule wrightii*, and *Thalassia testudinum*) in the southern Indian River Lagoon and the lower CRE (Buzzelli et al. 2012, Buzzelli et al. 2014a, 2014b).

The *Vallisneria* model was previously used to evaluate the salinity conditions that led to net annual mortality (Component Study 8, **Appendix A**). This reevaluation expanded on this earlier work. The base model output (1998–2014) was used to evaluate the duration of high salinity exposure (number of consecutive days when salinity $\geq$ 10), which led to decreased *Vallisneria* shoots versus the duration of low salinity conditions (number of consecutive days where salinity < 10) required for recovery.

Component Study 7 (**Appendix A**) includes an analysis of the relationship between the number of consecutive days where salinity at Ft. Myers was $\geq$ 10 and the percentage of initial *Vallisneria* shoots remaining at the end of each high salinity period at Sites 1 and 2 in the CRE (**Figure 31**).

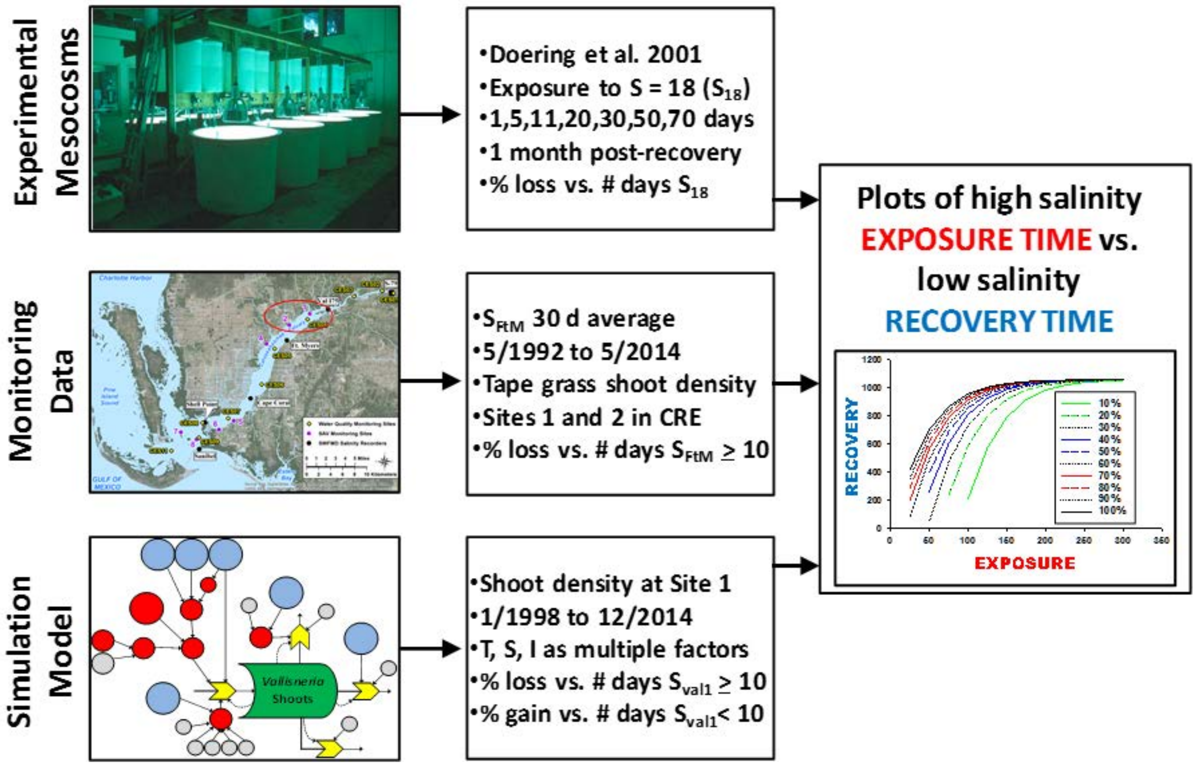


Figure 31. Schematic summarizing approach to derive exposure versus (vs.) response curves for *Vallisneria*. (Note: # – number; d – days, I – submarine irradiance, S – salinity, S_{18} – salinity of 18, S_{FtM} – salinity at the Ft. Myers station, S_{val1} – salinity at SAV monitoring Site 1, and T – water temperature.)

To further evaluate the duration element associated with the MFL criteria, the field monitoring data contained in Component 7 was evaluated with two additional sources of information (mesocosm and model). All three sources were analyzed similarly to derive a combined curve showing high salinity exposure duration that is significantly harmful to *Vallisneria*. First, data from mesocosm experiments designed to quantify the effects of high salinity exposure time on *Vallisneria* were used to derive a similar relationship (Doering et al. 2001). The independent variable for this relationship was the number of consecutive days where salinity = 18, or the salinity treatment for the mesocosm experiment. Second, the base output from the *Vallisneria* model was similarly analyzed. Since the model was developed for SAV monitoring Site 1 in the upper CRE, the output was parsed for all time periods where salinity was ^{3} 10 (**Figure 32**). The duration of each discrete high salinity period was plotted versus the corresponding percent decrease in shoot density. The results from each of the approach (field, mesocosm, and model) were merged to generate a mathematical relationship between the number of consecutive days when salinity ^{3} 10 and the relative (%) loss of *Vallisneria* shoots (**Figure 33A**). The exposure relationship between the duration of high salinity conditions and the percent shoots remaining derived from the three approaches was fit to an exponential decay equation with a half-life of 26 days (r^2 = 0.81; **Figure 33B**).

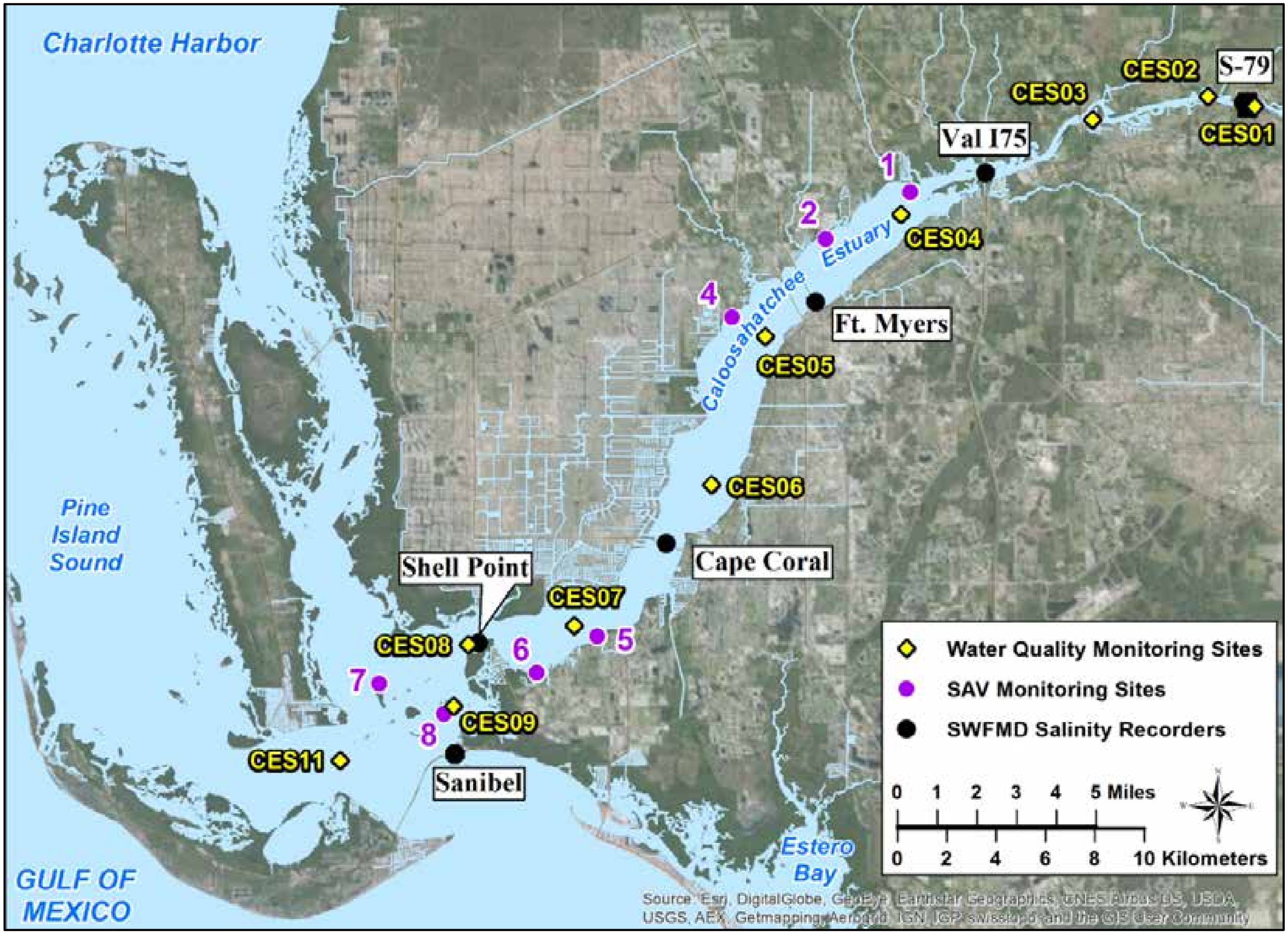


Figure 32. Location map for water quality, SAV, and salinity monitoring sites in the CRE.

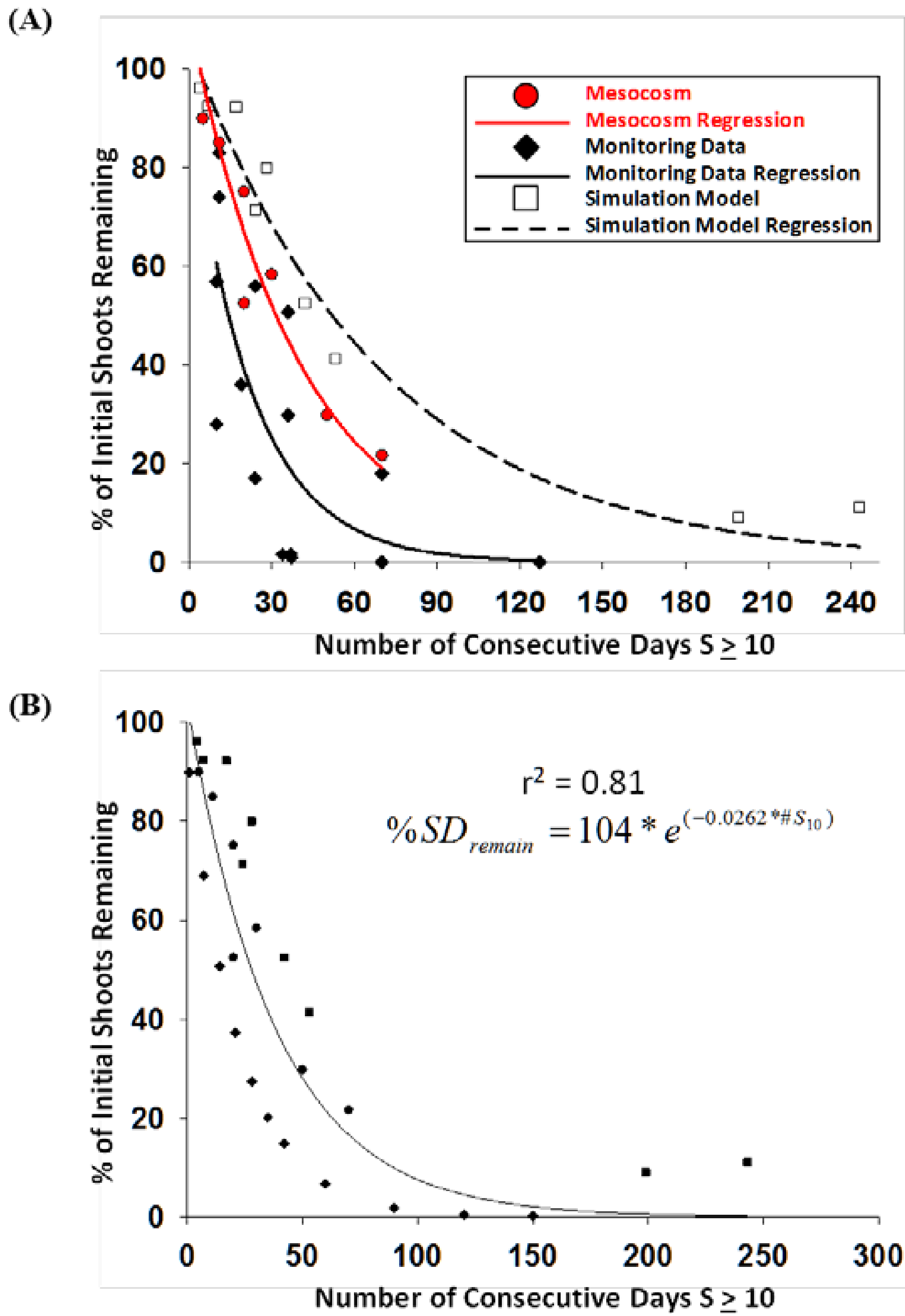


Figure 33. (A) Three separate high salinity (S) exposure duration curves for *Vallisneria* in the CRE (field, mesocosm, and model). (B) Composite decay curve for *Vallisneria* response to high salinity duration. (Note: The plot in A depicts the number of consecutive days where salinity ³ 10 versus the percent of initial shoots remaining.)

The contiguous daily model output provided the best pathway to quantify the duration of low salinity conditions required for *Vallisneria* to recover a relative fraction of shoots following high salinity exposure. Thus, the percent increase in shoot density was plotted versus the duration of salinity values < 10 at Site 1 for each period. The recovery relationship between the relative increase in shoot density and the number of consecutive days when salinity < 10 at Site 1 was fit to a hyperbolic function that saturated at approximately 900 days ($r^2 = 0.72$; **Figure 34**). Merging the exposure and recovery equations simultaneously (**Figures 33B** and **34**, respectively) facilitated the determination of the unfavorable salinity duration that could significantly harm the resource (e.g. *Vallisneria* habitat).

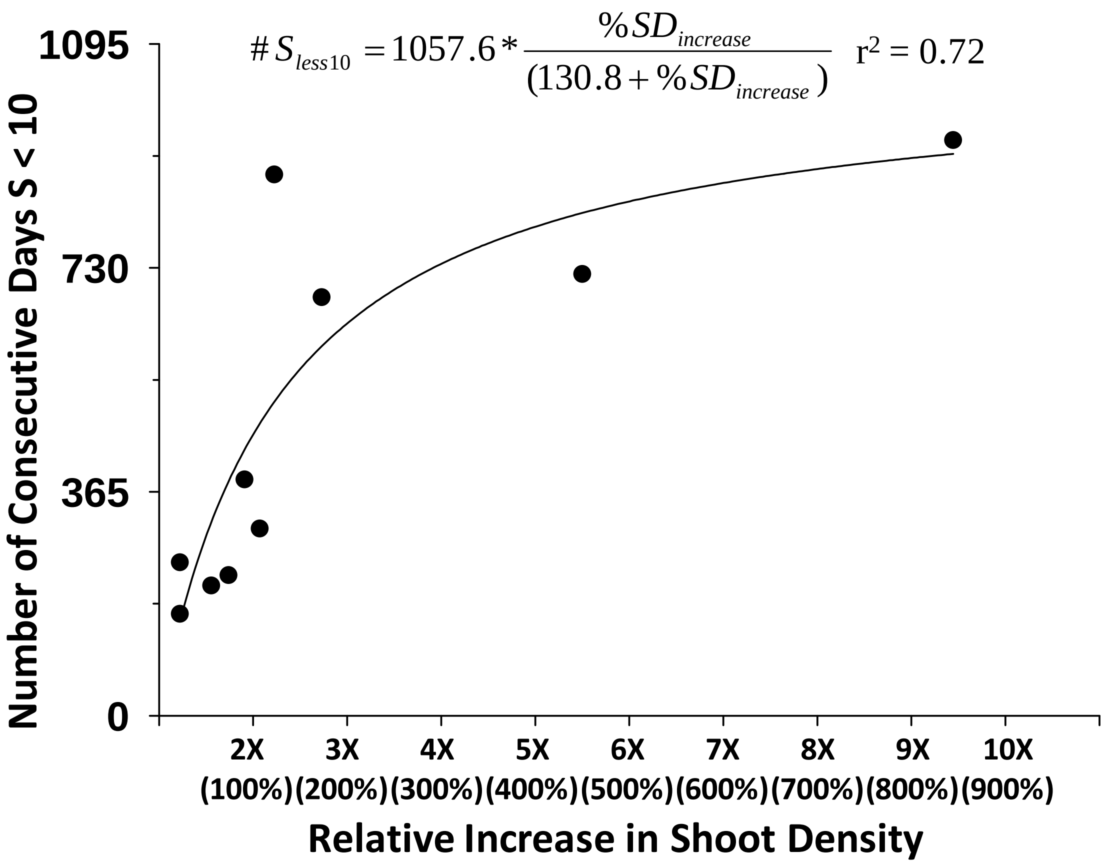


Figure 34. *Vallisneria* recovery curve composed of the relative increase in *Vallisneria* shoot density (SD) versus the number of consecutive days where salinity (S) < 10.

The exposure and recovery equations were solved to produce a family of curves to predict the duration of low salinity conditions (Site 1 salinity < 10) required to recover from a particular duration of high salinity condition (Site 1 salinity ≥ 10). The multiple curves were required to span a range of target recoveries from 10 to 100% of shoots (**Figure 35**). Therefore, if significant harm is defined as the environmental harm from which two years (730 days) are required to recover, then *Vallisneria* should experience no more than 55 consecutive days of salinity > 10 (dashed line **Figure 35**).

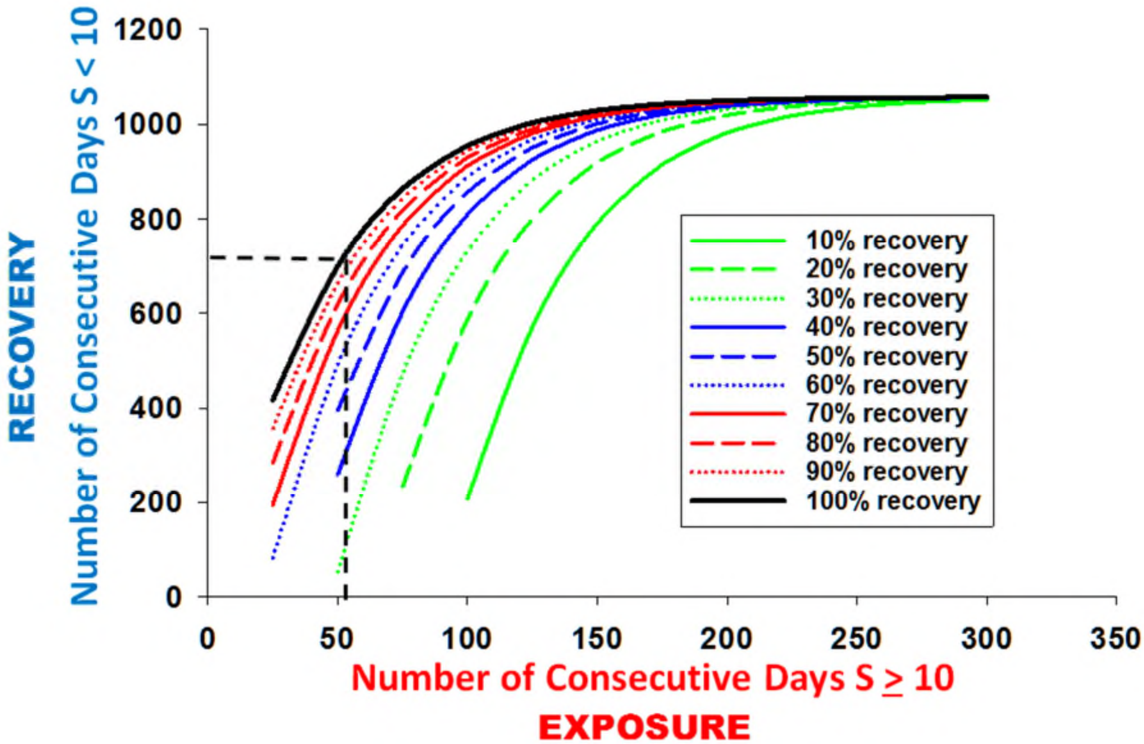


Figure 35. Merged exposure versus recovery curves over a range of potential levels of recovery (10 to 100%). (Note: The dashed line indicates that two years of recovery time is required if *Vallisneria* is exposed to high salinity [S] conditions for 55 days.)

RETURN FREQUENCY

The return frequency is the number of times that minimum flows can be expected to occur naturally as a function of climatic variation over time. Flows at S-79 are affected by natural variation in rainfall, local management of watershed resources, and the regional management derived from the regulation of Lake Okeechobee water level. Owing to these anthropogenic influences, analysis of flows is unlikely to yield the best estimate of a natural return frequency. Instead, rainfall was analyzed since it drives flow and is directly influenced by climatic variation.

Spectral analyses of dry season rainfall for the Tidal Caloosahatchee Subwatershed (WY1914–WY2016) and the C-43 Watershed (WY1914–WY2013) upstream of S-79 were conducted. A non-linear regression relationship between dry season flow at S-79 (y) and dry season rainfall upstream of S-79 (x) for the POR (WY1967–WY2013) was then derived. Dry season rainfall associated with estimates of minimum flows at S-79 were calculated. The drought recurrence interval of rainfall associated with each estimate of minimum flow was determined using a ranking approach (Stedinger et al. 1993; **Table 11**). Finally, the results of Component Study 10 (blue crab) (**Appendix A**) provided additional estimates of return frequency using spectral and Monte Carlo analyses of annual catch data and dry season rainfall.

Minimum inflows of 365, 380, and 400 cfs were associated with 6.81, 7.14, and 7.55 inches, respectively, of rainfall in the dry season (**Table 11**). The drought recurrence intervals were 6.0, 5.4, and 5.1 years, respectively. The blue crab fisheries information from Component 10 (**Appendix A**) were used in the return frequency analysis because the study links the magnitude of minimum flow to the 2-year recovery period contained in the definition of significant harm. The return frequency information obtained from the Monte Carlos and spectral analysis are consistent with the drought recurrence interval associated with the minimum flow of 400 cfs (**Table 11**). Monte Carlo analysis for blue crabs estimated that minimum inflows occurred with 7.1 inches of dry season rainfall and a 5.8-year recurrence interval (**Table 11**). Accompanying spectral analysis resulted in return frequencies of 5.3 to 5.6 years (**Table 12**).

Table 11. Estimates of the drought recurrence interval for dry season rainfall in the C-43 Watershed associated with estimates of minimum flows at S-79. (Note: Also given is the rainfall and recurrence interval associated with significant harm determined from the blue crab Monte Carlo analysis.)

Minimum Flow (cfs)	Rainfall (inches)	Drought Recurrence Interval (years)
365	6.81	6.0
380	7.14	5.4
400	7.55	5.1
Blue Crab Monte Carlo Analysis	7.1	5.8

Table 12. Summary of periodicity in annual blue CPUE and dry season rainfall in Lee County and the C-43 Watershed determined from spectral analysis.

	Periodicity (years)
Blue Crab CPUE and Dry Season Rainfall	5.6
Lee County	5.6
C-43 Watershed	5.3

SPECIFICATION OF THE MINIMUM INFLOW RATE FOR THE CRE

A framework now exists for the specification of an MFL for the CRE. This framework was based on the information gained in the *Assessment of the Responses of the Caloosahatchee River Estuary to Low Freshwater Inflow in the Dry Season* (**Appendix A**), the information in this chapter, and auxiliary data sources. The framework provides a magnitude, a duration, and a return frequency.

A freshwater inflow rate of 400 cfs should serve as the **magnitude** of the minimum inflow rate to the CRE. This value was derived through multiple avenues of analysis and interpretation. First, analysis of long-term blue crab harvest data for Lee County, rainfall, and freshwater inflows targeted the definition of significant harm for the CRE (Component Study 10). This analysis provided a minimum inflow rate of 400 ± 57 cfs in the dry season (**Figure 29**). Second, the median value among 11 estimates of Q_I was 400 cfs (**Table 10**).

The **duration** of unsuitable environmental conditions associated with minimum freshwater inflow at S-79 was determined to be > 55 consecutive days of salinity values equal to or greater than 10 at the Ft. Myers station. This duration was derived using *Vallisneria* exposure and recovery equations. This duration estimate is consistent with the definition of significant harm where the resource requires two years to recover. A combination of field, mesocosm, and simulation model results pertaining to *Vallisneria* were incorporated to derive this value.

The **return frequency** is the number of times in a given period of time that minimum flows can be expected to occur naturally. The return for the rainfall associated with a flow of 400 cfs at S-79 is 5.1 years. Therefore, it is reasonable to anticipate at least one climatically-driven exceedance of the minimum flow in a five-year period.

Based on the above analyses, SFWMD staff recommend the following MFL criteria for the CRE:

- The minimum flow is a mean monthly flow of 400 cfs measured at the S-79 structure.
- An MFL exceedance occurs during a 365-day period when the 30-day moving average flow at S-79 declines below 400 cfs and the daily average salinity at the Ft. Myers station has exceeded 10 for more than 55 consecutive days.
- An MFL violation occurs when an exceedance occurs more than once in a five-year period.

Chapter 8 evaluates whether these recommended criteria are being met under existing and future conditions.

CHAPTER 7: DESCRIPTION AND APPLICATION OF MODELS THAT RELATE DRY SEASON FRESHWATER INFLOWS TO SALINITY

INTRODUCTION

Anthropogenic and natural changes originating within coastal waters and their watersheds can influence both ecosystem structure and function. However, direct impacts are often difficult to predict using cause-and-effect relationships from observation or monitoring programs alone. The observed changes are usually the result of multiple variables or stressors under the compounding effects of various physical driving forces. This complexity makes the evaluation of water resources management and its impact on the coastal ecosystems difficult. SFWMD takes an integrated physical and ecological modeling approach for critical initiatives like the MFL Program and Comprehensive Everglades Restoration Plan (CERP)-related projects, to meet multiple water management objectives for the protection and restoration of coastal ecosystems (Wan et al. 2006, Buzzelli et al. 2015). An integrated modeling approach consists of linked models used to simulate the effects of changes in population, land use, or management practices in the watershed on estuarine physics, chemistry, and ecology. Model results are holistically evaluated in a context of integrated management of the land-ocean continuum. Specifically, the regional and watershed models estimate the quantity, timing, and quality of freshwater inflow to the estuary. The estuarine hydrodynamic model then simulates the estuarine conditions in terms of salinity. Finally, the ecological models simulate the responses of estuarine resources and processes to the estuarine conditions.

Evaluation of recommended MFL criteria and a recovery strategy for the CRE was greatly aided by integration of a suite of hydrologic and ecological models simulating (1) long-term freshwater inflow associated with varying management options, (2) the resulting salinity in the estuary, and (3) ecological response of indicator species that are sensitive to low freshwater inflows. Five models were specifically utilized, including three models for simulations of freshwater inflows to the CRE (two for S-79 flows and one for flows from the Tidal Caloosahatchee Subwatershed), a three-dimensional hydrodynamic salinity model, and a tape grass model (**Figure 36**). The three models simulating freshwater inflows include (1) the South Florida Water Management Model (SFWMM) to simulate freshwater discharges at S-79, which includes regional operations of Lake Okeechobee and incorporates Caloosahatchee irrigation demands; (2) the C-43 Reservoir Model uses the SFWMM-simulated daily S-79 flow as input and simulates the management benefit of the C-43 Reservoir; and (3) the Watershed (WaSh) Model to simulate tidal tributary inflow downstream of S-79. The Caloosahatchee Hydrodynamic/Salinity Model is based on the Curvilinear Hydrodynamic Three-dimensional Model (CH3D) modeling framework with the functionality of simulating the spatial salinity structure across the entire estuary. The Tape Grass Model takes the CH3D modeled salinity as input to simulate the tape grass growth at critical locations in the estuary pertaining to the development of MFLs. A 41-year POR (1965 to 2005) was modeled to ensure that a wide range of climatic conditions was included. The purpose of this chapter is to provide a brief introduction of these models and describe how these models were used for the MFL reevaluation.

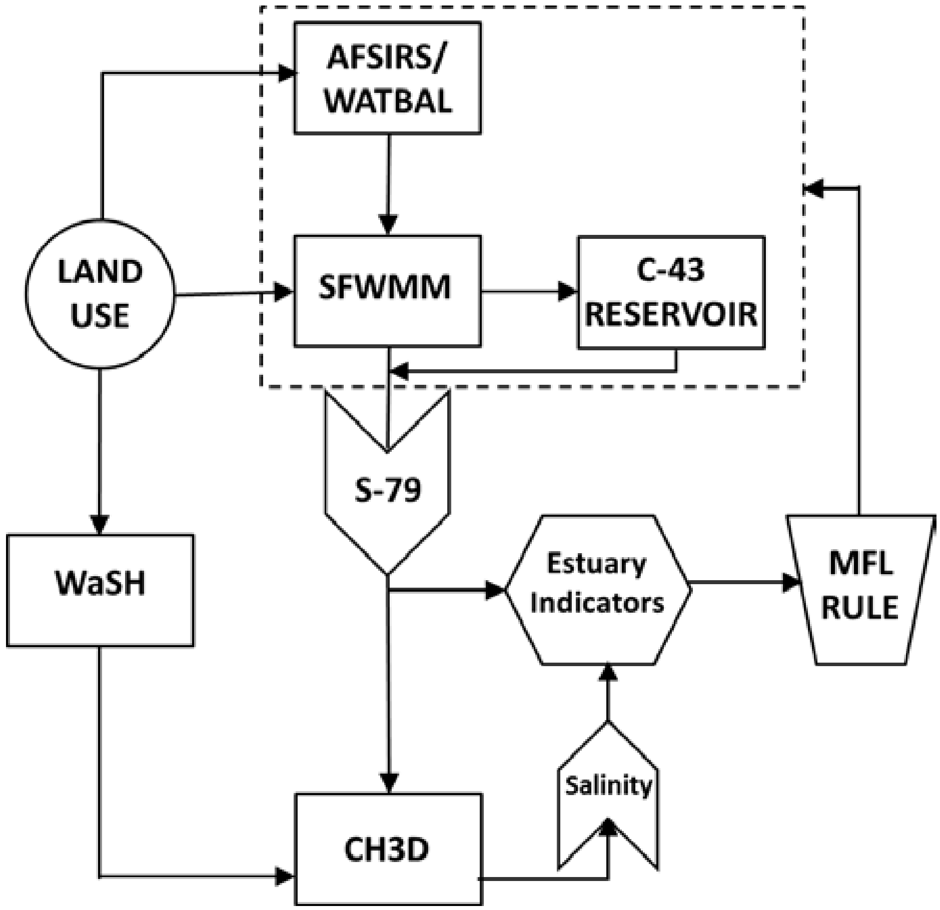


Figure 36. Integrated hydrologic and ecological models for the CRE MFL reevaluation. (Note: WaSH – Watershed Model, AFSIRS/WATBAL - Agricultural Field Scale Irrigation Requirements Simulation/Water Balance, SFWMM – South Florida Water Management Model, C-43 Reservoir – C-43 Reservoir Model, S-79 – S-79 Structure, and CH3D – Curvilinear Hydrodynamic Three-dimensional Model [Hydrodynamic/Salinity Model].)

FRESHWATER INFLOW MODELS

South Florida Water Management Model

The South Florida Water Management Model (SFWMM) is a regional-scale hydrologic model that simulates the hydrology and management of the water resources system from Lake Okeechobee to Florida Bay, covering 7,600 square miles (**Figure 37**). The model simulates the major components of South Florida's hydrologic cycle on a daily basis using climatic data from 1965 to 2005. The components include rainfall, evapotranspiration, infiltration, overland and groundwater flow, canal flow, canal-groundwater seepage, levee seepage, and groundwater pumping. The SFWMM incorporates current water management control structures and current operational rules and these operations remain the same throughout the 1965- 2005 POR. A major strength of this model is its ability to simulate water shortage policies affecting urban, agricultural, and environmental water uses. The SFWMM is widely accepted as the best available tool for analyzing operational changes to the complex water management system in South Florida and provides information for making the most effective water management decisions.

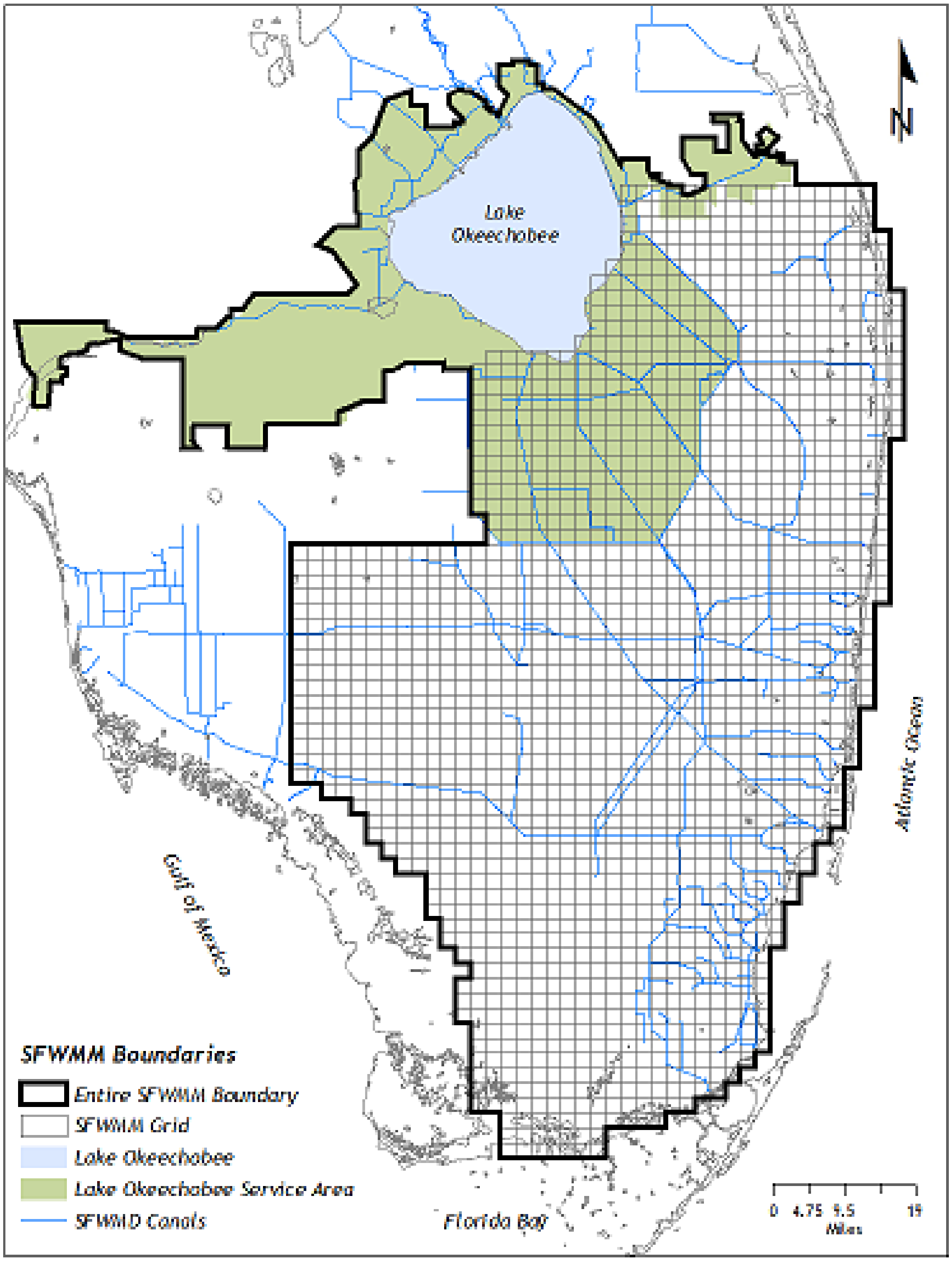


Figure 37. The SFWMM model domain.

The SFWMM uses output from the Agricultural Field Scale Irrigation Requirements Simulation/Water Balance (AFSIRS/WATBAL) model as input to represent the hydrology of watersheds surrounding Lake Okeechobee known collectively as the Lake Okeechobee Service Area. AFSIRS/WATBAL is a watershed-scale, simple water budget model based on the Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS) model (Smajstrla 1990).

The AFSIRS Water Budget spreadsheet was developed to calculate and route runoff and groundwater components for AFSIRS. The WATBAL spreadsheet calculates the hydrology of non-irrigated land. The Caloosahatchee implementation of AFSIRS/WATBAL has been updated and includes existing and future scenarios for this effort. All major components of the hydrologic cycle are determined in AFSIRS/WATBAL: (1) demands from groundwater and surface waters, (2) demands for the major irrigated and non-irrigated land uses, and (3) runoff from land irrigated with groundwater, from land irrigated with surface water, and non-irrigated lands. The water budget modeling for a given basin has three primary separate components: AFSIRS, AFSIRS Water Budget, and Water Balance (WATBAL).

The Caloosahatchee implementation of the AFSIRS/WATBAL model is conceptualized as four areas defined by geography and water source covering the lands between S-77/S-235 and S-79 that influence the regional system (**Figure 38**). These areas are grouped as the East Caloosahatchee Subwatershed irrigated with groundwater, East Caloosahatchee Subwatershed irrigated from the C-43 Canal, West Caloosahatchee Subwatershed irrigated with groundwater, and West Caloosahatchee Subwatershed irrigated from the C-43 Canal. The break between the "East" and "West" Caloosahatchee subwatersheds is considered to occur at the S-78 structure. This conceptualization of the model requires additional spreadsheets to handle the routing between these four areas. Also, the Caloosahatchee implementation has the supplementary consideration of public water supply withdrawals from the C-43 Canal (Lee County and Fort Myers) and deliveries from the regional system (Lake Okeechobee, C-43 Reservoir, aquifer storage and recovery [ASR], etc.) to supplement agricultural and public water supply withdrawals. The model was calibrated for the period from 1991 to 2000 and its parameters are used in single-area implementations of other Lake Okeechobee Service Area areas. The S-4 East Disston Island implementation is a single area AFSIRS/WATBAL model, which is a subset of the S-4 Subwatershed. The S-4 Other AFSIRS/WATBAL implementation represents the remainder of the S-4 Subwatershed not inside the East Disston island subunit. Each implementation provides daily watershed runoff and irrigation demands to the SFWMM. The SFWMM is run and then provides existing and future baseline flows to the C-43 Reservoir Model, which modifies S-79 flows (magnitude and timing) for evaluation of the MFL criteria and recovery strategy.

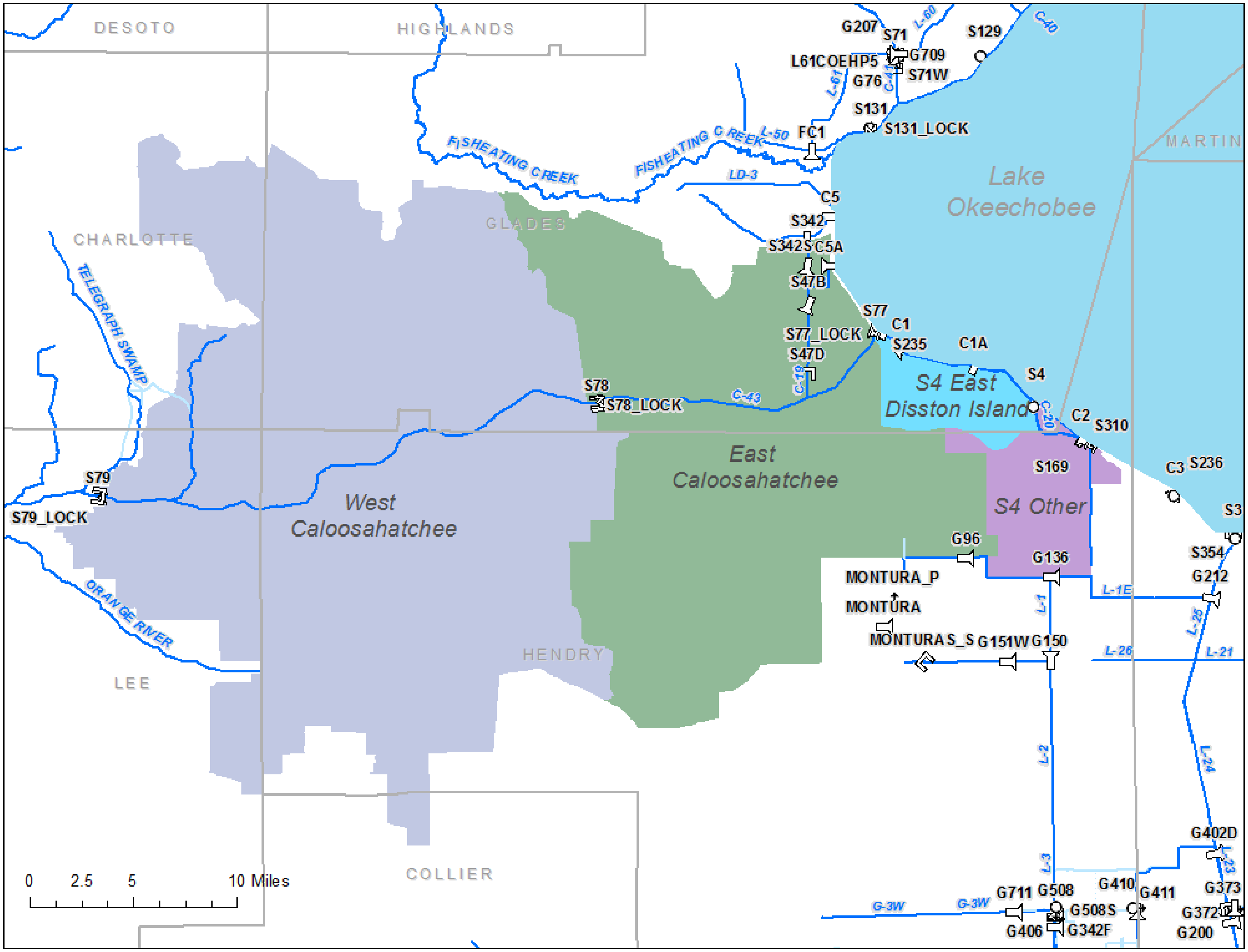


Figure 38. The model domain of the AFSIRS/WATBAL hydrologic model in the portion of the CRE MFL Watershed upstream of S-79.

C-43 Reservoir Model

The proposed C-43 Reservoir is expected to provide additional storage allowing increased operational flexibility in controlling discharges to the CRE. To illustrate the potential performance associated with this project for CERP, a spreadsheet model was developed using a 41-year period of simulation (1965- 2005). The spreadsheet's primary goal is to compare the CERP with-project discharge over S-79 (the downstream point at which the watershed discharges into the estuary) to the preproject discharge over S-79 and an estuary target time series representing restoration target flows over S-79 for a daily time step. These restoration flows were addressed in the *Central and Southern Florida Project, Comprehensive Everglades Restoration Plan Caloosahatchee River (C-43) West Basin Storage Reservoir Project Final Integrated Project Implementation Report and Final Environmental Impact Statement* (USACE and SFWMD 2010). In addition, the spreadsheet shows a water budget for the reservoir and tracks reservoir inflows, releases, and storage.

The reservoir operations are optimized to make the best of the water available and to prolong availability during the dry season. The operations vary by season and for empty and full water levels (see **Appendix C**). A screening-level analysis was performed using the minimum flows of 300, 365, 380, 400, 450, and 650 cfs. For each run, the minimum operations for release criteria were set from 0 cfs to each of the values listed. The six daily sets of S-79 flows were delivered to the evaluation team and the team chose 300 and 400 cfs to evaluate further. The screening-level flow targets in the 450 to 650 range were considered restoration targets while the flow targets between 365 and 400 cfs were difficult to distinguish from a scientific standpoint because the responses were similar for multiple ecological indicators. However, after considering concerns associated with impingement of zooplankton at S-79 and significant harm to the blue crab fishery, a flow target of 400 cfs was chosen. The target flow of 300 cfs represents the existing MFL criterion and was chosen for comparison with the recommended MFL criterion. The chosen runs were then finalized and documented herein.

The latest operational criteria developed in the preliminary design process of the reservoir will be used with modifications to minimum flows. Two runs were performed where the minimum flows were set to 300 and 400 cfs instead of 0 cfs, as in the project implementation report (PIR; USACE and SFWMD 2010). These minimum values are maintained daily if water is available in the reservoir. Please see **Appendix C** for detailed model assumptions and reservoir operations.

The application of the C-43 Reservoir Model described above is for a different purpose than the model application contained in the CERP PIR (USACE and SFWMD 2010). The model application used for this MFL reevaluation, with a target flow of 300 or 400 cfs at the S-79 structure, was designed to evaluate the minimum flow necessary to prevent significant harm in the CRE. The model application used for PIR involved a restoration time series to achieve full restoration of the CRE. See **Appendix C** for a detailed table of assumptions and reservoir operations.

Modeling Assumptions

Two baselines of AFSIRS/WATBAL were run to produce current and future time series of Caloosahatchee (combined East and West), S-4 East Disston Island, and S-4 Other demand and runoff from 1965 to 2005. These time series were then used in two SFWMM runs to represent an Existing Condition Baseline (ECB) and Future Condition Baseline (FCB). From the two SFWMM baselines, time series of flows at the S-79 structure are extracted. The S-79 data are used as input to the C-43 Reservoir Model, which sends these flows to the reservoir when there is available storage and sends flows from the reservoir to S-79 structure during drier times. The reservoir is modeled as in the CERP with minor changes to minimum deliveries for the MFL (300 and 400 cfs). See **Appendix C** for a detailed table of assumptions and reservoir operations.

Documentation of Demands

Current Demands (2012)

Demands for the C-43 Watershed (**Figure 38**) were estimated using Lake Okeechobee Service Area permitted water use boundaries as of February 2012. See *Lake Okeechobee Service Area Consumptive Use Demands for the South Florida Water Management Model* (SFWMD 2012). Using ArcGIS, the permit boundaries with actual planted acreages were combined with land use information to model the agriculture in production. Current CERP project boundaries were also included to represent areas not in agricultural production due to potential clearing and construction. The data were then divided into the model subwatersheds and the AFSIRS/WATBAL model was updated and run. **Table 13** provides a summary of land use types modeled in AFSIRS/WATBAL.

Table 13. AFSIRS/WATBAL modeled acreages for the Caloosahatchee Update. (Note: Includes Caloosahatchee East and West, S-4 East Disston Island, and S-4 Other; Nicodemus Slough Basin is not included in 2040 acreages.)

	Citrus	Cane	Vegetable	Pasture	Upland Forest	Wetland
2012	76,235	87,501	13,892	256,595	95,816	99,757
2040	83,583	102,424	7,310	247,782	68,443	85,700

Future Demands (2040)

Future (2040) irrigation projections for the East Caloosahatchee, West Caloosahatchee, and Tidal Caloosahatchee subwatersheds were developed using a combination of permit boundaries, public lands, county comprehensive plans, and Florida Statewide Agricultural Irrigation Demand data. The 2012 land use served as the base land use geographic information system (GIS) layer. The Nicodemus Slough Basin was removed due to a change in its hydrologic connection to the East Caloosahatchee Watershed. Each of the listed data sets were incorporated into the 2012 land use data set and used to query and establish future land use FLUCCS codes for urban, conservation, water storage, and agriculture land use types. The data were then divided into the model subwatersheds and the AFSIRS/WATBAL model was updated and run. See **Table 13** for a summary of land use types modeled in AFSIRS/WATBAL.

Model Simulations

Existing Condition Base without Project

The SFWMM was used to produce a 2012 baseline that represents 2012 demands with current system operations. AFSIRS/WATBAL used Lake Okeechobee Service Area data from February 2012 (SFWMD 2012, 2013). The C-43 Reservoir was not modeled in this run. See **Appendix C** for full list of assumptions.

Existing Condition Base with Project (300 cfs)

The C-43 Reservoir Model uses the S-79 daily flows from the ECB without Project from the SFWMM as input. The model then fills and empties the 9,380-ac reservoir based on operations defined by CERP. For this simulation, the minimum flows were changed from 0 to 300 cfs. See **Appendix C** for full list of reservoir operations and assumptions.

Existing Condition Base with Project (400 cfs)

This model run is the same as described above with one change. For this simulation, the minimum flows were changed from 0 to 400 cfs. See **Appendix C** for full list of reservoir operations and assumptions.

Future Condition Base without Project

The SFWMM was used to produce a 2040 baseline using updated AFSIRS/WATBAL demand and runoff output for the Caloosahatchee area (combined East and West Caloosahatchee subwatersheds), S-4 East Disston Island, and S-4 Other areas located upstream of S-79. Current operations of the SFWMD system are modeled and the A-1 Reservoir as modeled in the Central Everglades Planning Project (CEPP) is included to simulate flows south, which will affect water levels in Lake Okeechobee and flows to the CRE. The C-43 Reservoir is not modeled in this simulation. See **Appendix C** for full list of assumptions.

Future Condition Base with Project (300 cfs)

The C-43 Reservoir Model uses the S-79 daily flows from the FCB without Project from the SFWMM as input. The model then fills and empties the reservoir based on operations defined by CERP. For this simulation, the minimum flows were changed from 0 to 300 cfs. See **Appendix C** for full list of reservoir operations and assumptions.

Future Condition Base with Project (400 cfs)

The C-43 Reservoir Model uses the S-79 daily flows from the FCB without Project from the SFWMM as input. The model then fills and empties the reservoir based on operations defined by CERP. For this simulation, the minimum flows were changed from 0 to 400 cfs. See **Appendix C** for full list of reservoir operations and assumptions.

Model Results and Reservoir Performance

The C-43 Reservoir provides beneficial timing and magnitude of flows to the CRE. During high flow events, some excess water can be stored in the reservoir to reduce stressful events in the CRE. The reservoir also helps maintain a minimum flow to benefit the CRE during dry times and avoid high salinity conditions. **Figures 39** and **40** show that the reservoir increases the amount of months that water is available to meet the minimum deliveries to the estuary for the ECB. **Figures 41** and **42** show flow exceedance curves with 300-cfs and 400-cfs minimum flows for the ECB with and without reservoir, and the PIR restoration target. The 300-cfs run (**Figure 41**) shows that the reservoir is able to meet this minimum delivery 99% of the time. The 400-cfs run (**Figure 42**) shows that the reservoir is able to meet the minimum delivery 97% of the time. **Figures 43** and **44** show that the reservoir increases the amount of months that water is available to meet the minimum deliveries to the estuary for the FCB. **Figures 45** and **46** show flow exceedance curves with 300-

cfs and 400-cfs minimum flows for the FCB with and without the reservoir, and the PIR restoration target. The 300-cfs run (**Figure 45**) shows that the reservoir is able to meet this minimum delivery 98% of the time. The 400-cfs run (**Figure 46**) shows that the reservoir is able to meet the minimum delivery 96% of the time.

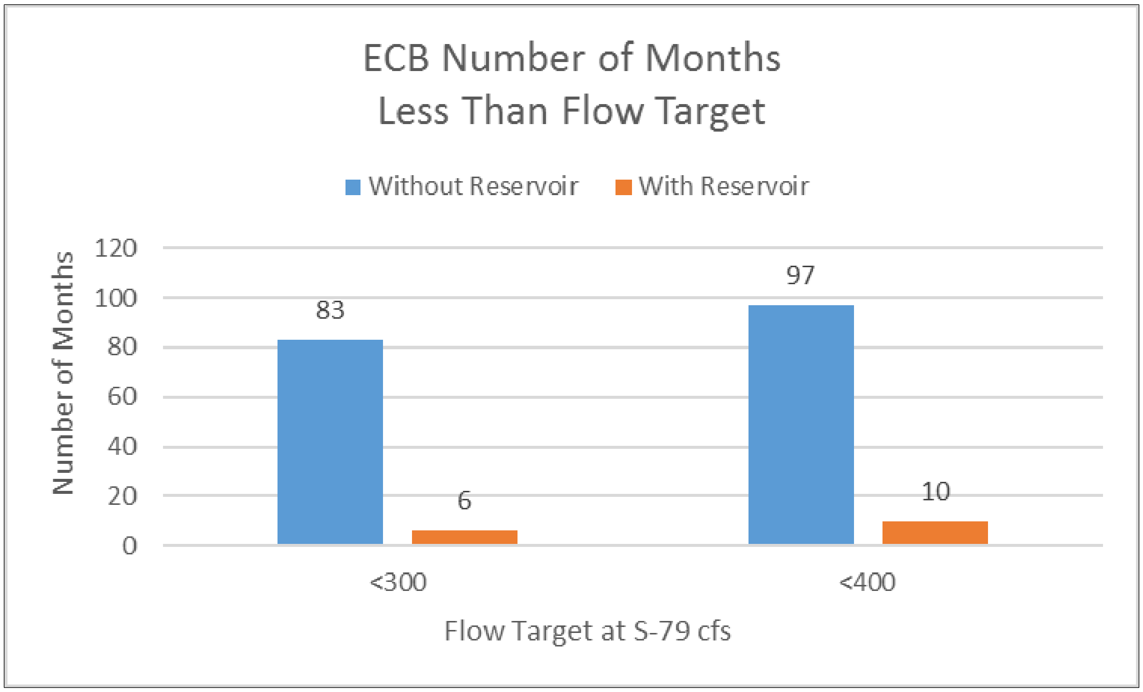


Figure 39. Number of months flow was less than the ECB targets of 300 and 400 cfs with and without the reservoir.

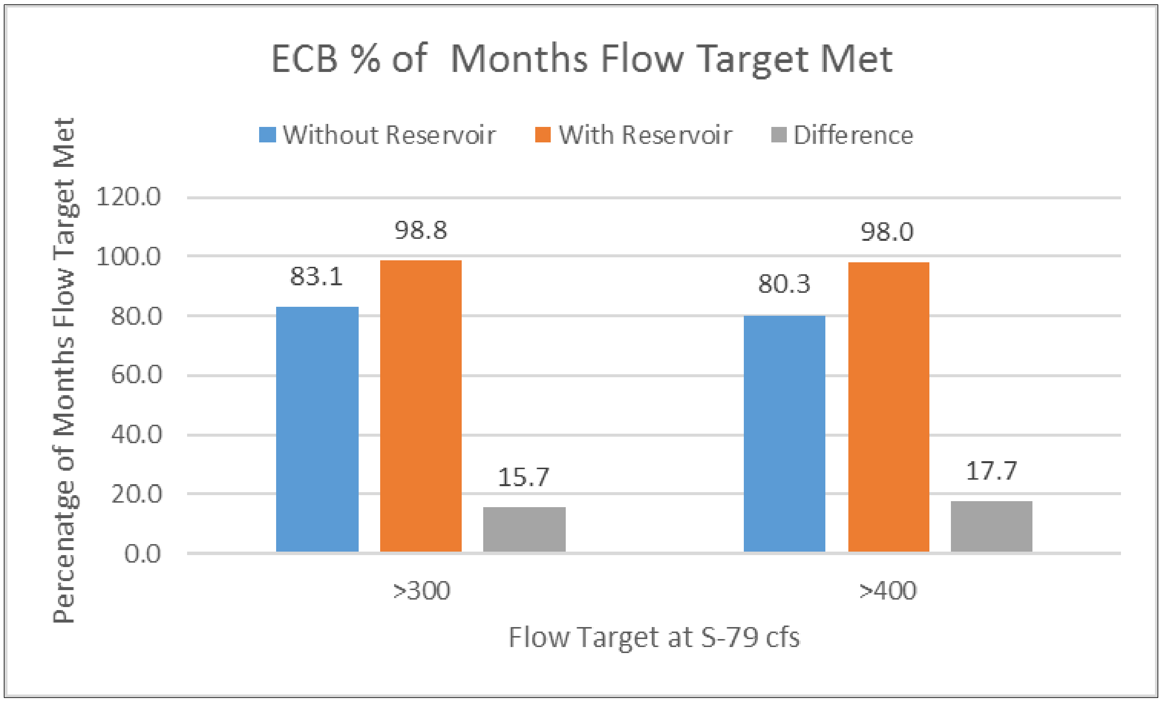


Figure 40. Percent of months the ECB targets of 300 and 400 cfs were met with and without the reservoir.

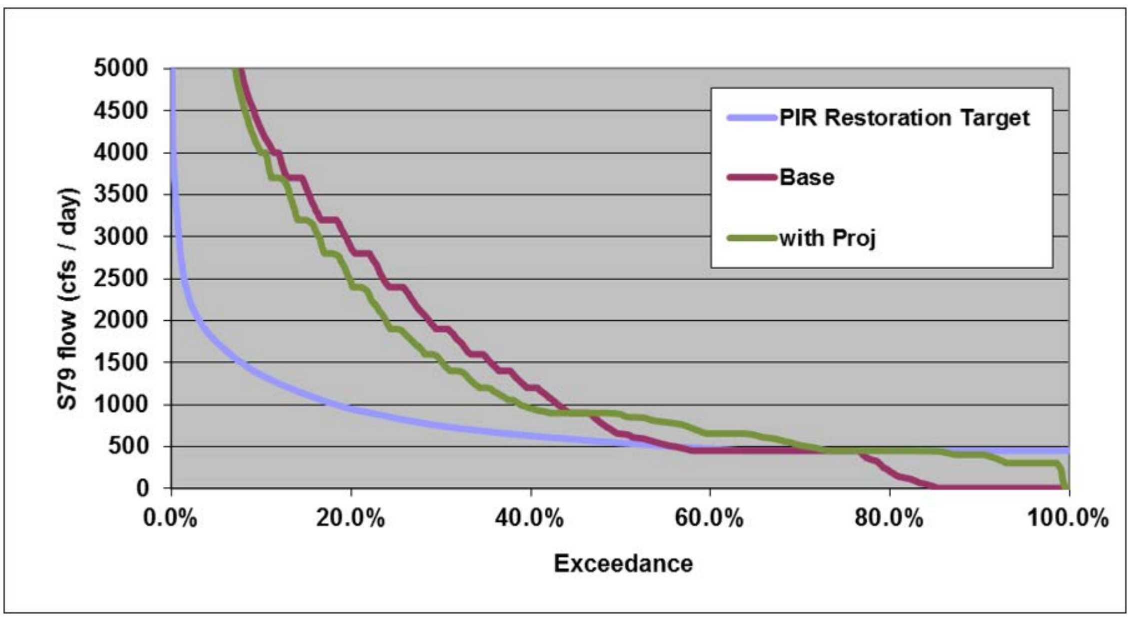


Figure 41. Flow exceedance curves for the ECB, the 300-cfs minimum with project (Proj), and the PIR restoration target.

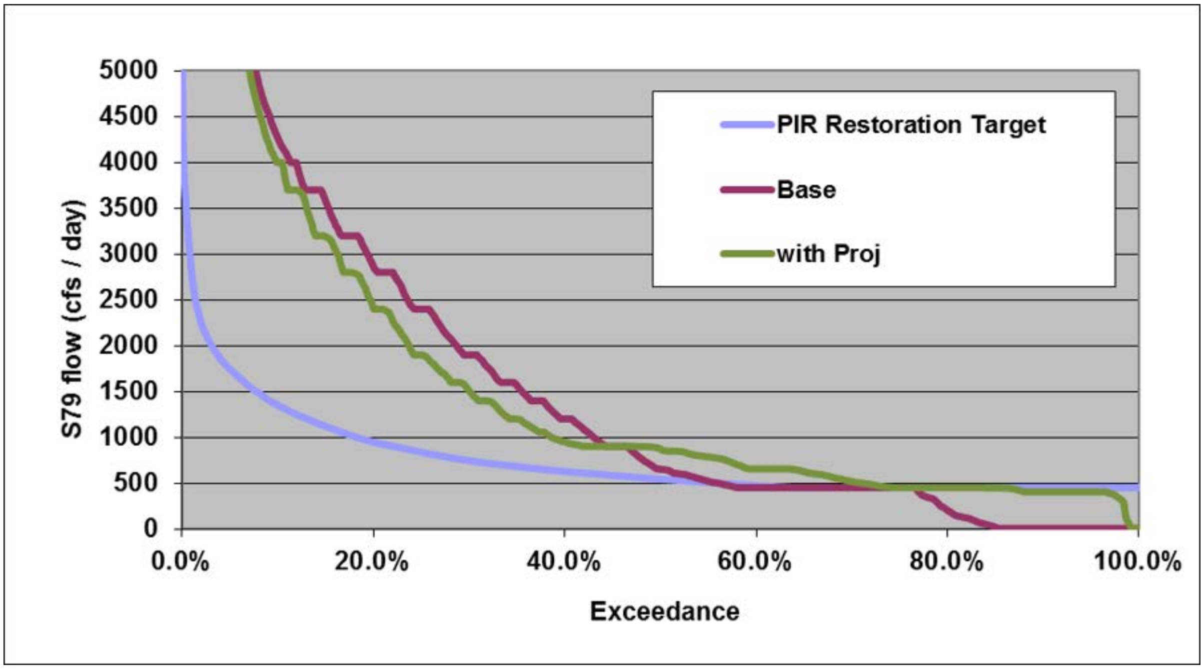


Figure 42. Flow exceedance curves for the ECB, the 400-cfs minimum with project (Proj), and the PIR restoration target.

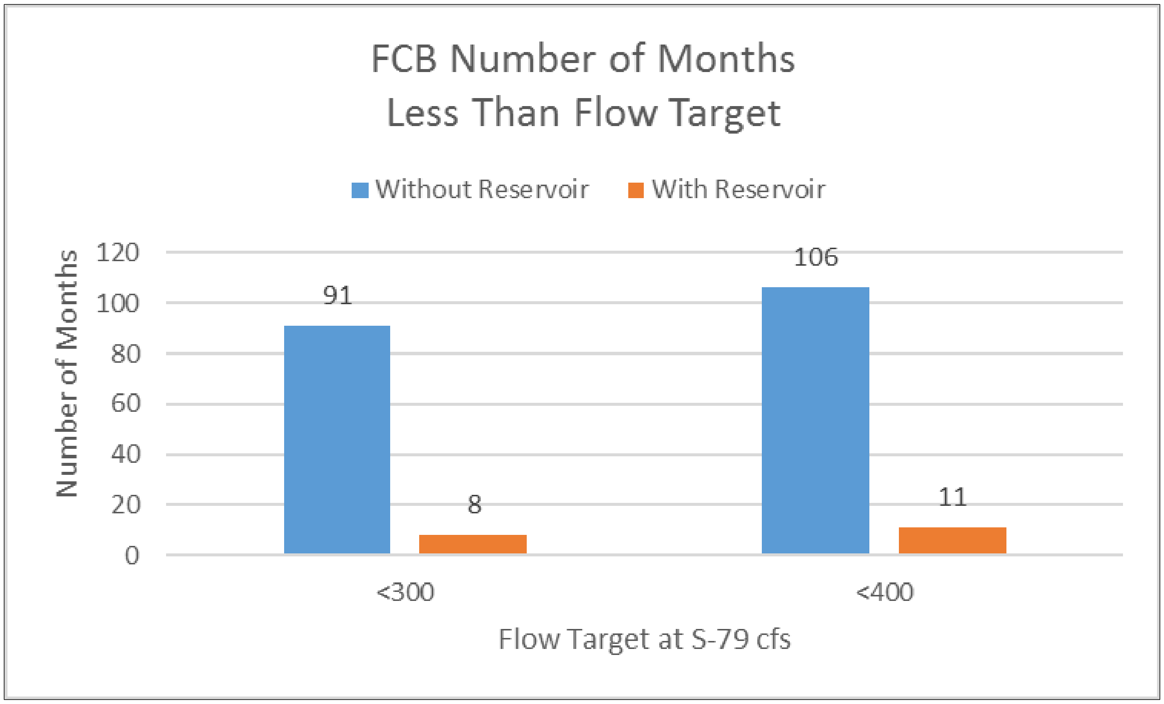


Figure 43. Number of months flow was less than the FCB targets of 300 and 400 cfs with and without the reservoir.

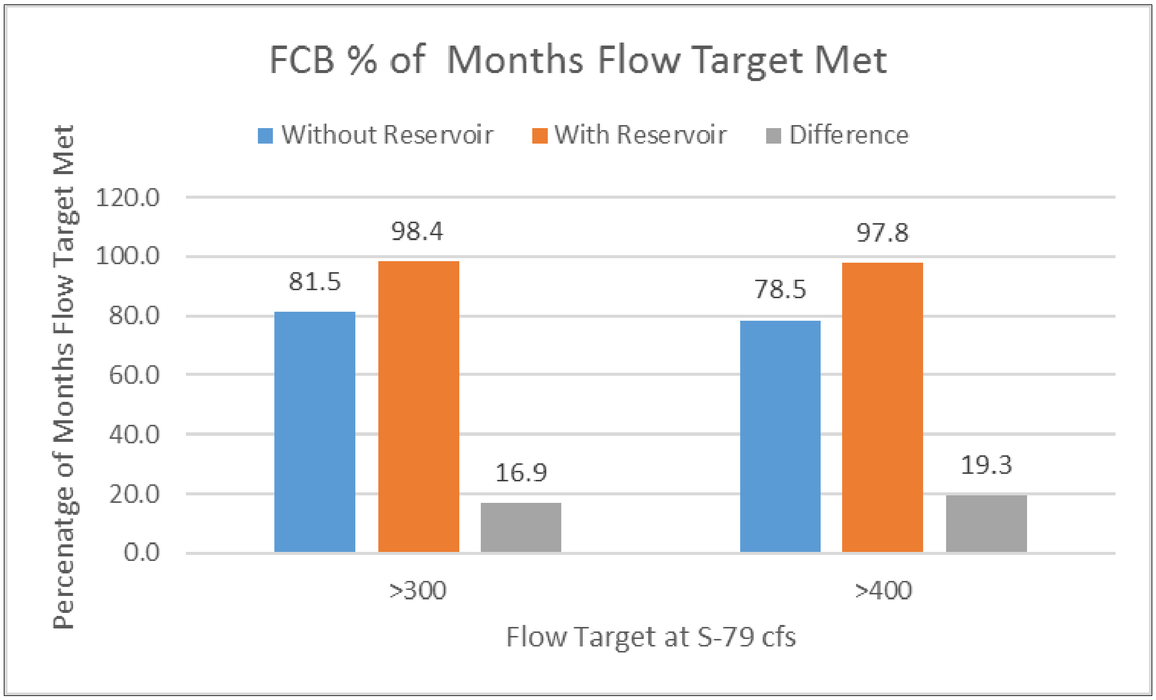


Figure 44. Percent of months the flow target was met for the FCB targets of 300 and 400 cfs with and without the reservoir.

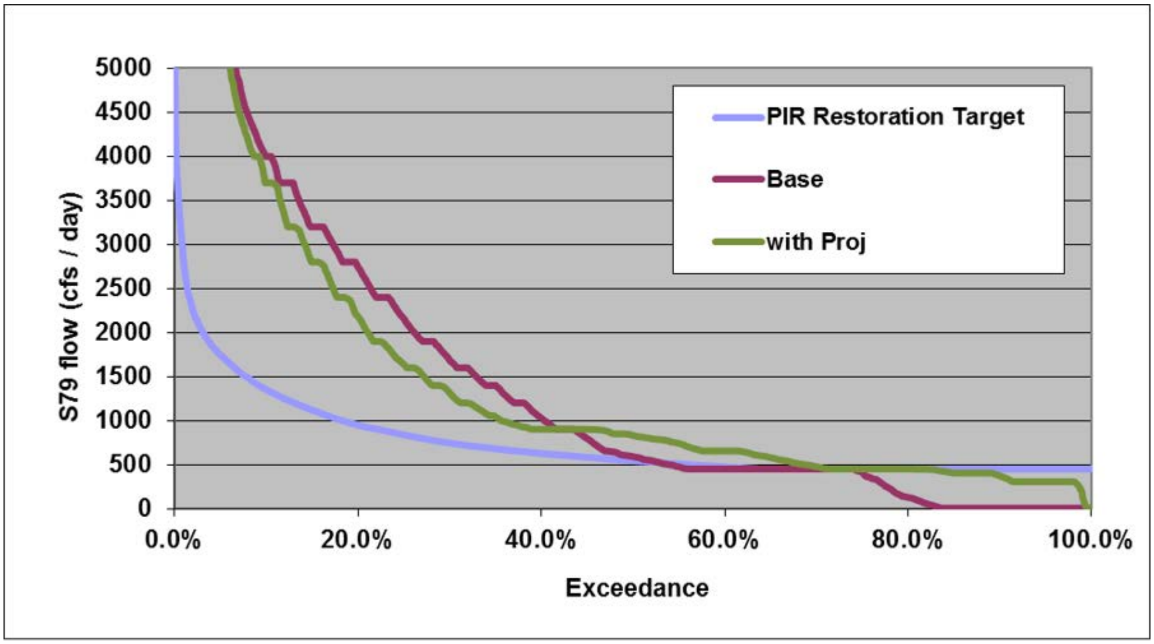


Figure 45. Flow exceedance curves for the FCB, the 300-cfs minimum with project (Proj), and the PIR restoration target.

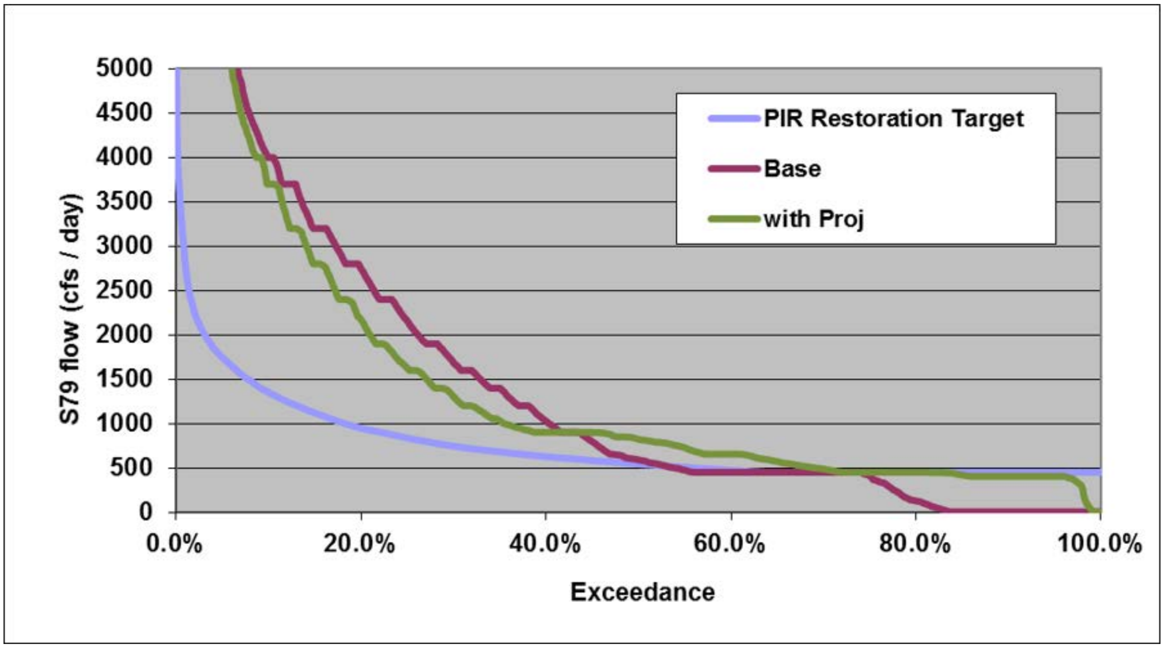


Figure 46. Flow exceedance curves for the FCB, the 400-cfs minimum with project (Proj), and the PIR restoration target.

TIDAL CALOOSAHATCHEE SUBWATERSHED WASH MODEL

The Watershed (WaSh) Model was developed based on restructuring the Version 12 Hydrologic Simulation Program – Fortran (HSPF) (Donigian et al. 1984) into a cell-based system with the addition of a groundwater model and a full dynamic channel routing model (URS Corporation 2003, AECOM 2016). The algorithms involved in HSPF was inherited from the Stanford Watershed Model (Crawford and Linsley 1996).

The WaSh model is capable of simulating hydrology in watersheds with high groundwater tables and dense drainage canal networks, which is typical in South Florida. The model consists of four basic components: (1) a cell-based representation of the subwatershed land surface, (2) a groundwater component consistent with the subwatershed 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 PWATER (hydrologic module for pervious area) and IWATER (hydrologic module for impervious area) modules from HSPF were utilized. The infiltrated water is routed to a groundwater model that represents the unconfined aquifer in the watershed. The groundwater model receives the infiltrated water and exchanges water between surface water and groundwater. 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 support branches, common flow structures, and tidal boundary conditions. The water quality component of WaSh was not implemented in this application. Key components of the WaSh model are summarized in **Table 14**.

Table 14. The WaSh Model components and functions.

Model Component	Modeling Approach	Functions
Surface Water Flow	PWATER and IWATER of HSPF	High water table algorithms of HSPF
Groundwater Flow	A new 2-dimensional unconfined groundwater flow model (Boussinesq Equation)	Canal drainage and recharge
Channel Flow	A new 1-dimensional fully dynamic shallow water dynamic wave model (St. Venant Equations)	Structures, branching, and point sources
Water Management	Reservoirs, stormwater treatment areas, irrigation supply and demands, and land use changes	Executed by an ArcGIS graphical user interface

Implementation of the WaSh model into the Tidal Caloosahatchee Subwatershed uses a uniform structured grid network of 3,000 ft x 3,000 ft (**Figure 47**) and length of reach segment of 2,000 ft. Each cell represents a discrete part of the model domain and has 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 length and width of canals in the cell are computed and added as a cell attribute. Generally, the cell attributes are obtained by combining the cell network with 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. The surface water and groundwater is modeled in the same grid network.

For each cell, WaSh uses the PWATER and IWATER modules of HSPF (Version 12) to simulate surface water hydrology (**Table 14**). The HSPF routine is implemented in a one-hour time step for 24-hour blocks. Thus, the HSPF-based routine is applied 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 surface water drainage canal network is modeled implicitly in the cell-based system with either weir-controlled flow or pump flow and explicitly in the reach-based system using one-dimensional full dynamic wave equations. The major channels are simulated in the reach-based system, which consists of a series of reaches and nodes. This drainage system is separated from the cell system, but its elements (reaches and nodes) overlay the cell network and coincide with a subset of the cells. This system is typically configured to follow the major canals, streams, and rivers in the subwatershed. 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. Groundwater flow is simulated by a standard groundwater flow Boussinesq Equation for an unconfined aquifer with Dupuit assumptions.

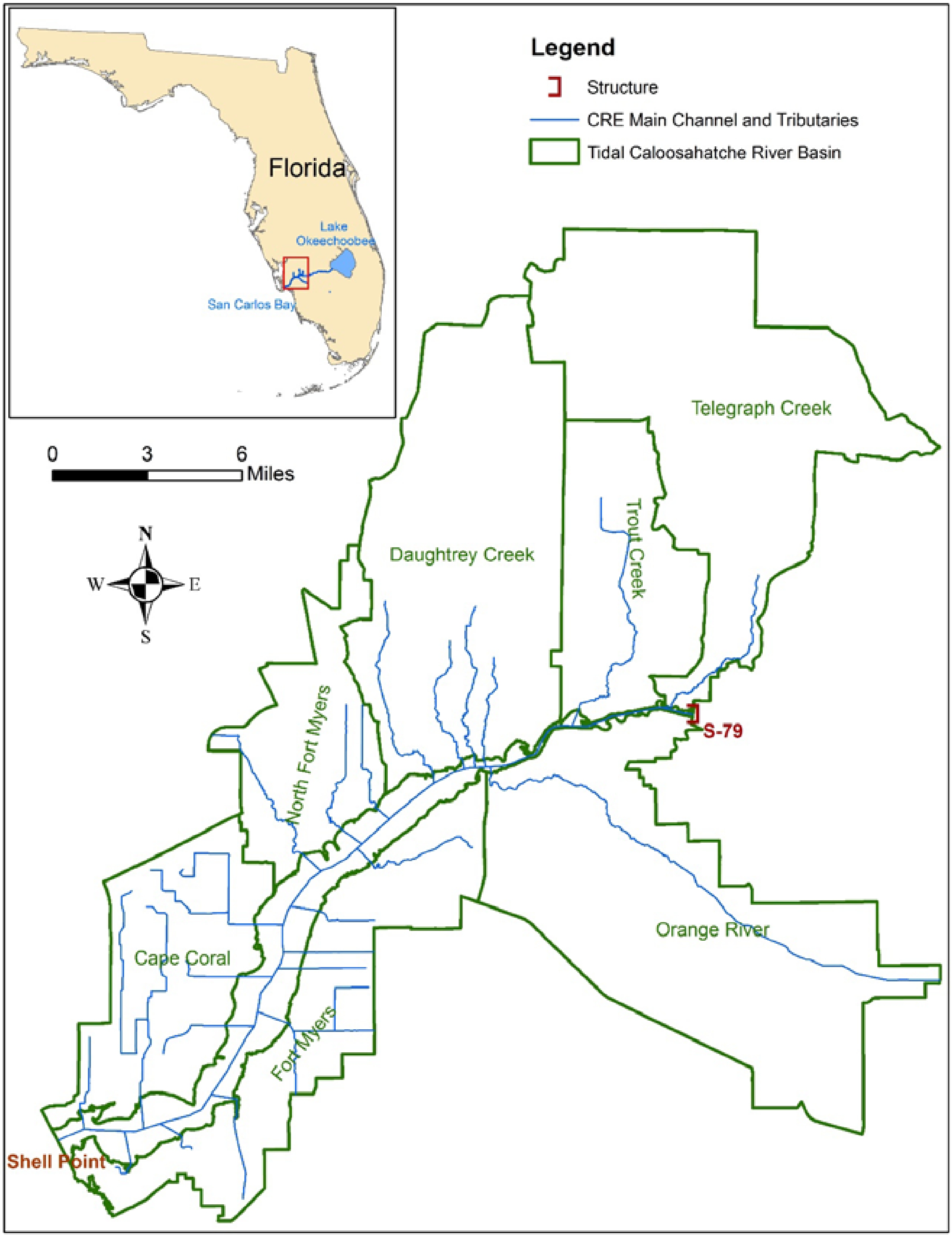


Figure 47. Domain of the Tidal Caloosahatchee Subwatershed WaSh Model.

The irrigation demand is monitored at the start of each day. To determine the irrigation demand, the model monitors the moisture in the root zone. When the moisture drops below a user specified percentage of the capacity, irrigation is triggered. The moisture deficit is the difference between the capacity and the actual moisture level.

FDEP, SFWMD, and USGS jointly conducted a flow monitoring program from October 2008 to March 2013 to measure stage and flow at several locations in the Tidal Caloosahatchee Subwatershed of the CRE (Telegraph Creek, Orange River, Popash Creek, Billy's Creek, Hancock Creek, Marker 52, and Shell Point). Lee County has monitored Whiskey Creek since April 1994. These data were collected to support further development and calibration of the Tidal Caloosahatchee Subwatershed Model.

This model was calibrated with hydrologic data from 2008 to 2010 and verified with data from 2011 to 2012. The 2009 land use data was used for model calibration and verification. The R^2 and Nash-Sutcliffe Efficiency (NSE) for model performance at eight flow gage stations are as follows: $0.64 < R^2 < 0.87$ and $0.57 < \text{NSE} < 0.84$ for calibration, and $0.51 < R^2 < 0.82$ and $0.412 < \text{NSE} < 0.79$ for verification. A detailed description of model development and simulation results evaluation can be found in **Appendix D.**

Then long-term (1967 to 2005) simulations using the Tidal Caloosahatchee Subwatershed Model were conducted using the 2012 land use data and 2040 land use. The simulation showed the percentage of inflow from the Tidal Caloosahatchee Subwatershed to total inflow to CRE is ~20% of total inflow for all seasons, ~17% in the dry season, and ~22% in the wet season. The simulated time series of freshwater inflow from the Tidal Caloosahatchee Subwatershed based on current and future land use condition were used as input to the CRE in the CH3D Hydrodynamic/Salinity Model (**Figure 48A**).

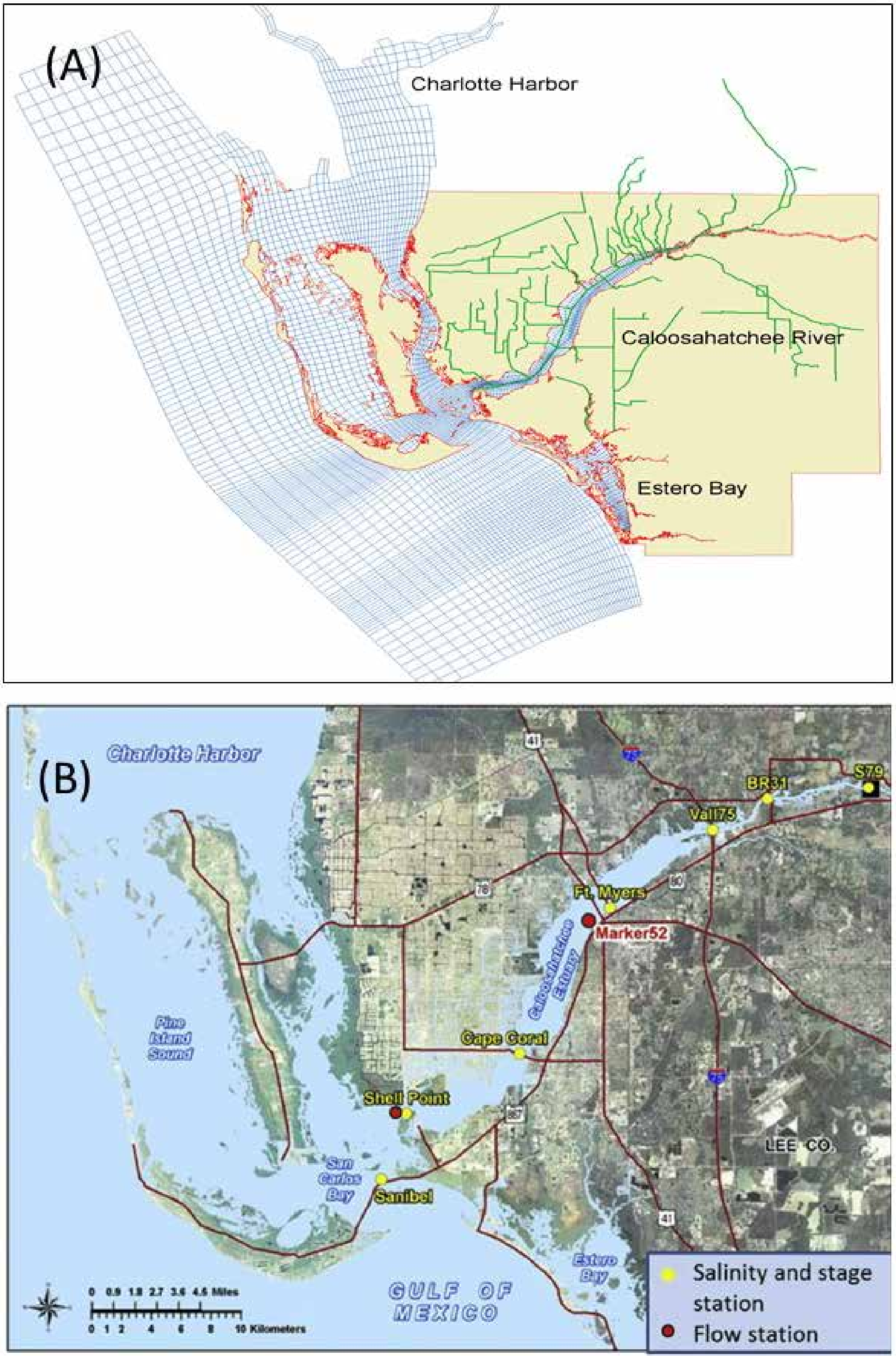


Figure 48. The CH3D CRE Hydrodynamic/Salinity Model (A) domain and (B) monitoring stations.

CH3D CRE HYDRODYNAMIC/SALINITY MODEL

Introduction

The CH3D CRE Hydrodynamic/Salinity Model is based on the Curvilinear Hydrodynamic Three-dimensional (CH3D) code, originally developed by Sheng (1986). It uses a horizontally boundary-fitted curvilinear grid and vertical sigma grid system capable of simulating complicated hydrodynamic processes including wind-driven, density-driven, and tidal circulation. The model contains a robust turbulence closure scheme for accurate simulation of stratified flows in estuaries and lakes (Sheng 1986, 1987, 1990, Sheng and Villaret 1989). The non-orthogonal nature of the model enables it to represent the complex geometry of an estuary such as the CRE. The model is driven by external forcing prescribed at the boundaries, including tidal forcing at the ocean boundary, freshwater inflow from controlled structures, runoff from the watershed, and meteorological forcing including wind and rainfall. Major assumptions for the CH3D CRE Hydrodynamic/Salinity Model are the hydrostatic assumption (shallow water equation), Reynold stress turbulence closure, and the log law boundary layer approximation at the bottom and surface (Sheng 1986).

The model domain covers the CRE, Charlotte Harbor, Pine Island Sound, San Carlos Bay, Estero Bay, and all the major tributaries (**Figure 48A**). The fine model grid permits the representation of the numerous islands, including the islands of the Sanibel Causeway. The horizontal grid has 163 x 120 cells. Inside the CRE and San Carlos Bay, higher resolution provides detailed representation of a complex shoreline and the navigation channel. The smallest grid size ranges from 50 to 100 m. Vertically, five evenly-spaced sigma-layers enable simulation of vertical stratification within the estuary. The original model development of CH3D in Charlotte Harbor and adjacent areas began in 1999 for the Charlotte Harbor National Estuary Program (Sheng 2002). SFWMD extended the 1999 CH3D model calibration to the CRE portion using a 16-month time series for the 2003 update of the MFL (Qiu 2002). In 2005, the CRE portions of the model were calibrated with three years of measured data (2001–2004) from 5 stations in the CRE (Qiu et al. 2007). Recently, the calibration of the model was further refined using newly collected salinity, tide, and flow data from 7 stations in the CRE (**Figure 48B**) (Sun et al. 2016).

The CH3D CRE Hydrodynamic/Salinity Model was used for three applications: (1) simulation of different flow scenarios and evaluation of flow target at S-79; (2) sensitivity study of sea level rise (SLR); and (3) evaluation of impact of physical alterations on salt transport in the CRE (see Study Component 1 in **Appendix A**).

Scenario Simulations and Evaluation of Flow Target

The CH3D CRE Hydrodynamic/Salinity Model was used to simulate salinity response to six discharge scenarios at S-79 (**Table 15**). The scenarios were designed for the comparison and evaluation of existing and future hydrological conditions, with and without the C-43 Reservoir, and different flow targets (300 and 400 cfs) at S-79. Detailed hydrology descriptions of these flow scenarios can be found in the *Model Simulations* section above. Daily salinity output at the Ft. Myers and Val I-75 monitoring stations from the model were then evaluated and compared for the six scenarios.

Table 15. Flow scenarios.

Abbreviation	Flow Scenario
ECBO	Existing Condition Baseline without reservoir
ECBW300	Existing Condition Baseline with reservoir, targeting 300 cfs at S-79
ECBW400	Existing Condition Baseline with reservoir, targeting 400 cfs at S-79
FCBO	Future Condition Baseline without reservoir
FCBW300	Future Condition Baseline with reservoir, targeting 300 cfs at S-79
FCBW400	Future Condition Baseline with reservoir, targeting 400 cfs at S-79

Model Setup

All the flow scenarios have a 41-year POR from January 1, 1965, to December 31, 2005. Setup of the hydrodynamic model was similar to that discussed in Component Study 1 (**Appendix A**). The boundary conditions included empirical inputs for water level at the ocean boundary, rainfall, and wind at the surface. Freshwater inflow at S-79 were provided by SFWMM and the C-43 Reservoir Model. Freshwater inflow from the Tidal Caloosahatchee Subwatershed runoff was provided by the WaSh Model for the ECB and FCB. The actual simulation period of the hydrodynamic model for each scenario was 39 years (January 1, 1967, to December 31, 2005), consistent with the model output period from the WaSh Model.

The major modeling assumptions included application of the same tidal boundary condition at the open boundary and the same meteorological forcing at the surface boundary for the existing and future conditions. The assumptions imply that climate changes including sea level rise (SLR) are not expected to have a significant impact on salinity in the estuary. The assumptions were partly justified by the fact that freshwater inflow is the dominant factor for salt transport in the estuary explaining more than 50% variation in daily salinity (Component Study 2 in **Appendix A**). They are also justified by model test results (see the following section), which suggest that salinity changes are insignificant in response to SLR for a range of SLR rates.

Simulation Results

Daily surface salinities at the Ft. Myers and Val I-75 stations were compared among the six scenarios (**Figures 49** and **50**). Statistics of high salinity events (salinity events) were calculated including the number of events for the POR, and the average duration and average salinity of the events (**Table 16**). A high salinity event is defined as a salinity greater than 10 for 55 or more consecutive days at the Ft. Myers station.

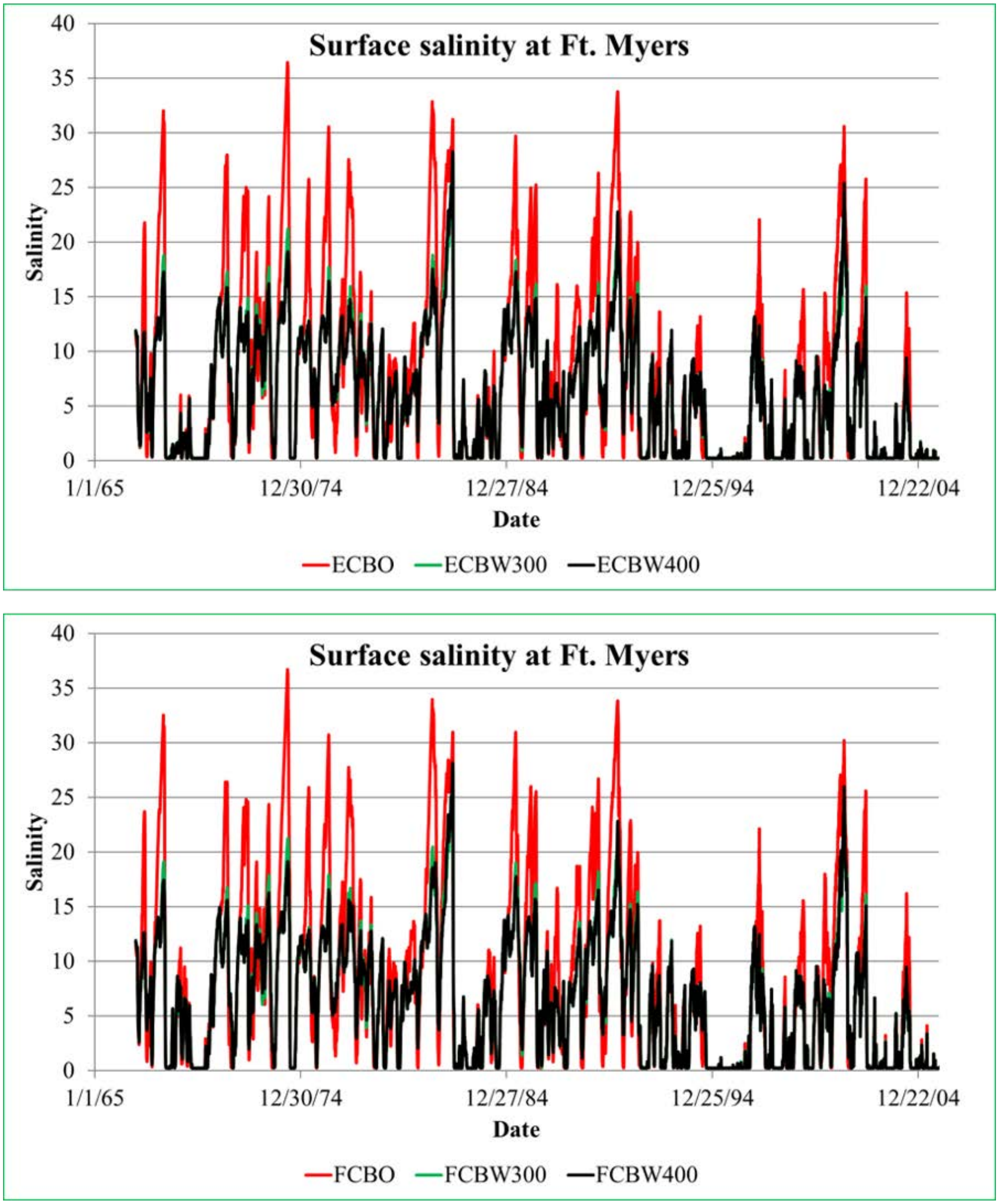
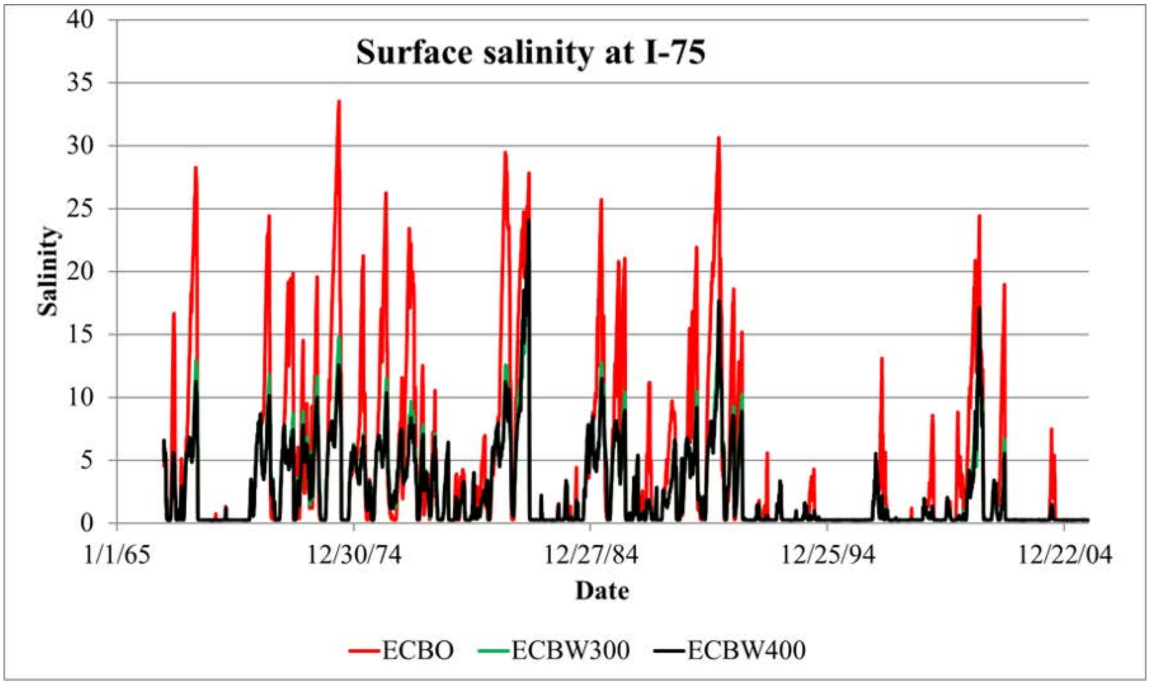


Figure 49. Surface salinity at the Ft. Myers station for the six flow scenarios.



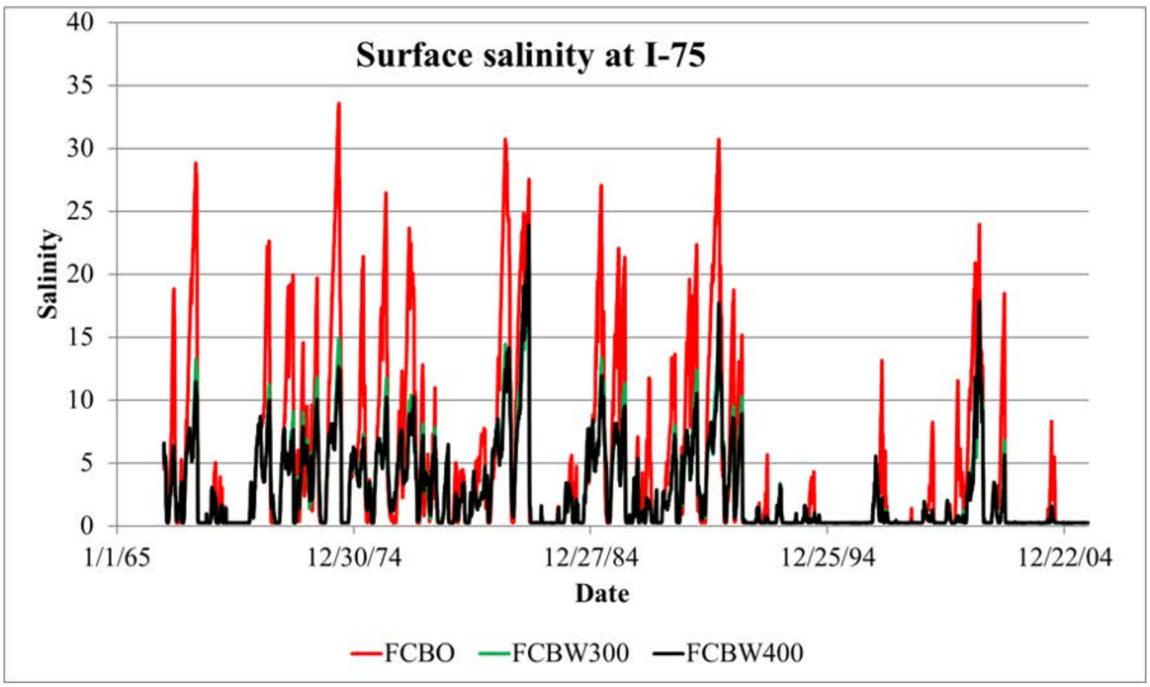


Figure 50. Surface salinity at the Val I-75 station for the six flow scenarios.

Table 16. Statistics of high salinity events at the Ft. Myers station.

Scenario	Number of Events	Average Duration (days)	Average Salinity
ECBO	23	163	19.5
ECBW300	24	139	13.77
ECBW400	24	138	13.54
FCBO	22	162	19.6
FCBW300	25	137	14.05
FCBW400	25	137	13.82

These model results suggest that there would be between 22 to 25 high salinity events during the 39-year simulation period (1967 to 2005). The number of events are similar among the six flow scenarios. However, the average duration of the events is significantly shorter with the reservoir than without the reservoir; the average salinity for the events are significantly lower with than without the reservoir. There appears to be insignificant differences between the 300-cfs targeted flow scenarios and 400-cfs targeted flow scenarios, except that salinities are slightly higher for the 300-cfs flow target than the 400-cfs flow target. The future hydrological condition may have slightly higher average salinity than the existing base conditions due to more competition for fresh water from other CERP projects expected to be completed in the future.

Based on the model results, the number of combined flow exceedance and high salinity events were computed for the eight flow scenarios (**Table 17** and **Figures 51** through **54**). These figures were produced to show when a flow exceedance and high salinity events occur simultaneously. These combined events occur when (1) monthly average flow at S-79 is less than the flow target, which is either 300 or 400 cfs; and (2) a high salinity event occurs at the Ft. Myers station.

Table 17. Number of combined flow exceedance events and high salinity events for the flow scenarios and two target flows.

Scenario	Flow	
	300 cfs	400 cfs
ECBO	23	24
ECBW	3	5
FCBO	22	23
FCBW	4	6

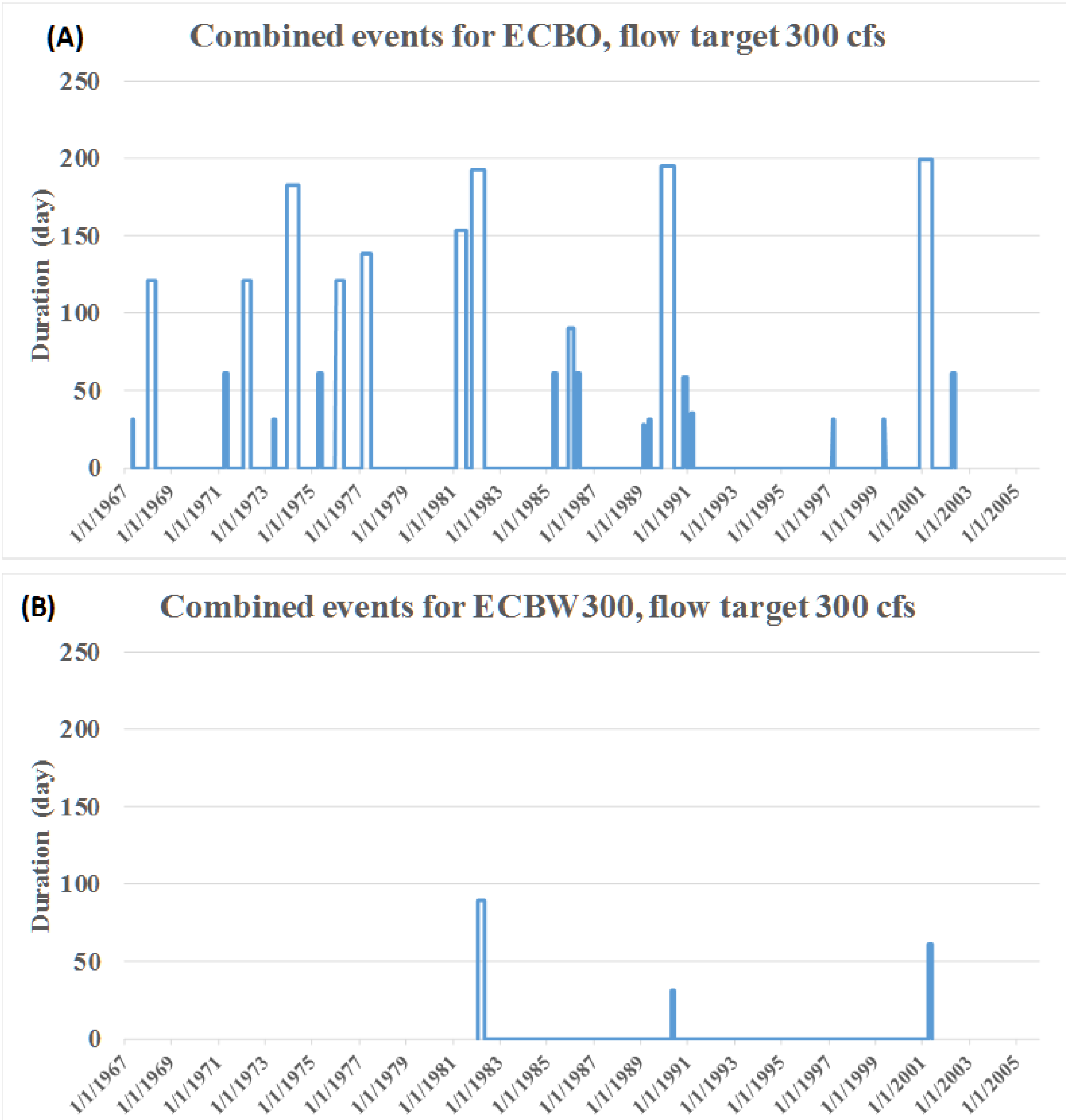


Figure 51. Combined flow exceedances and high salinity events for (A) ECBO and (B) ECBW300 with a target flow of 300 cfs. (Note: The location of each bar indicates the timing of the events, the number of the bars indicates the number of events, and the height of the bar indicates the duration of each event.)

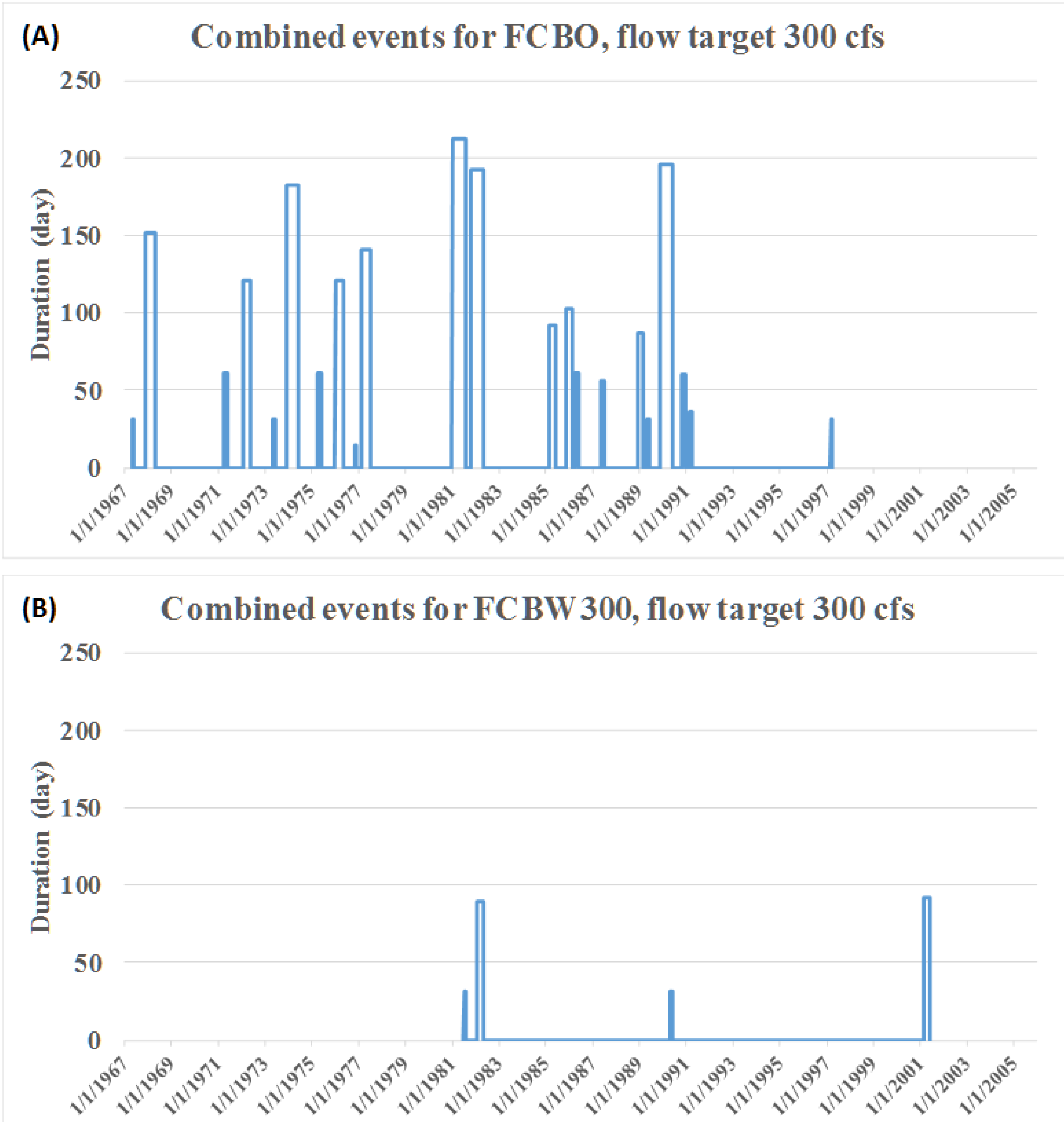


Figure 52. Combined flow exceedances and high salinity events for (A) FCBO and (B) FCBW300 with a flow target flow of 300 cfs. (Note: The location of each bar indicates the timing of the events, the number of the bars indicates the number of events, and the height of the bar indicates the duration of each event.)

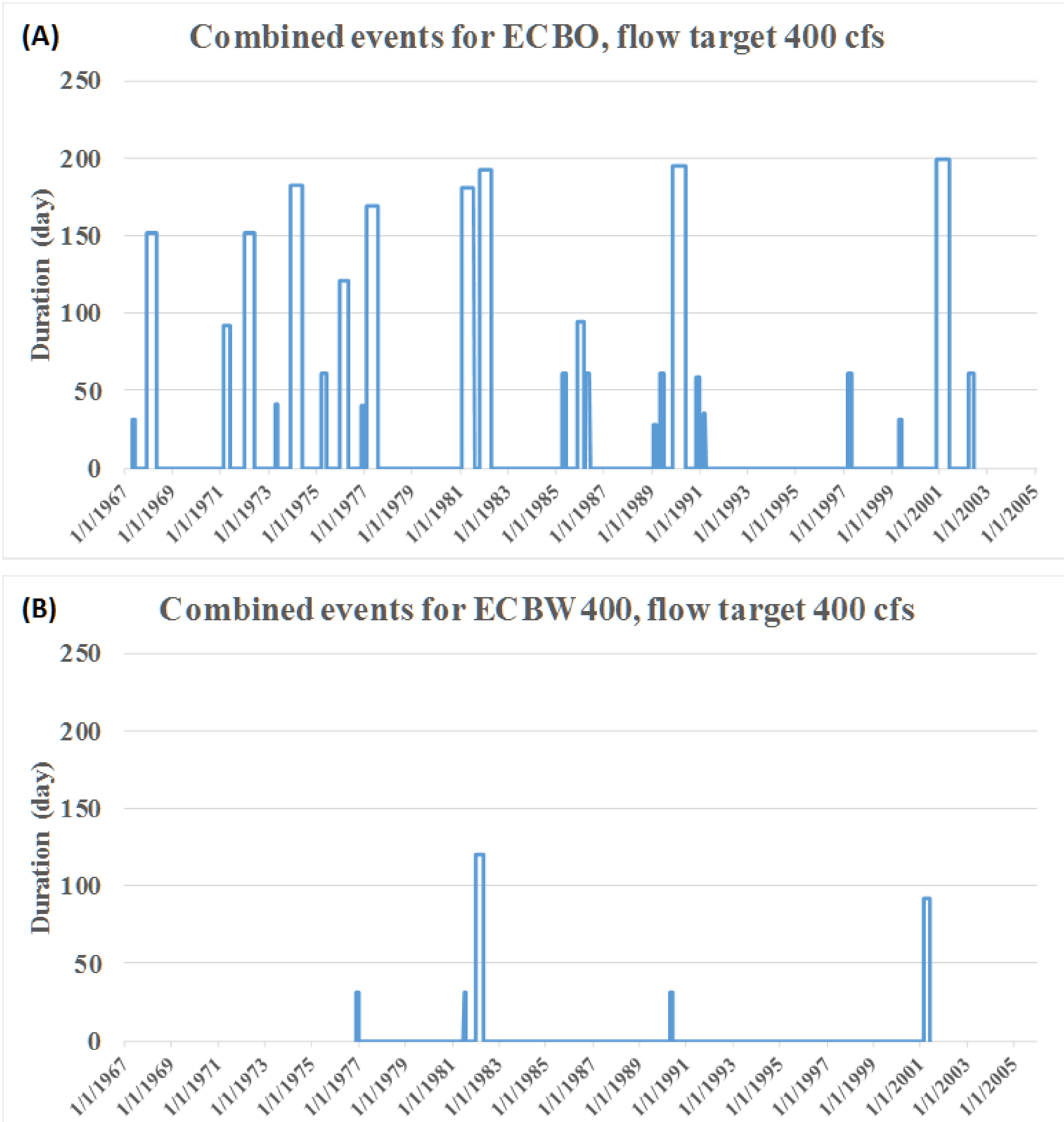


Figure 53. Combined flow exceedances and high salinity events for (A) ECBO and (B) ECBW400 with a flow target flow of 400 cfs. (Note: The location of each bar indicates the timing of the events, the number of the bars indicates the number of events, and the height of the bar indicates the duration of each event.)

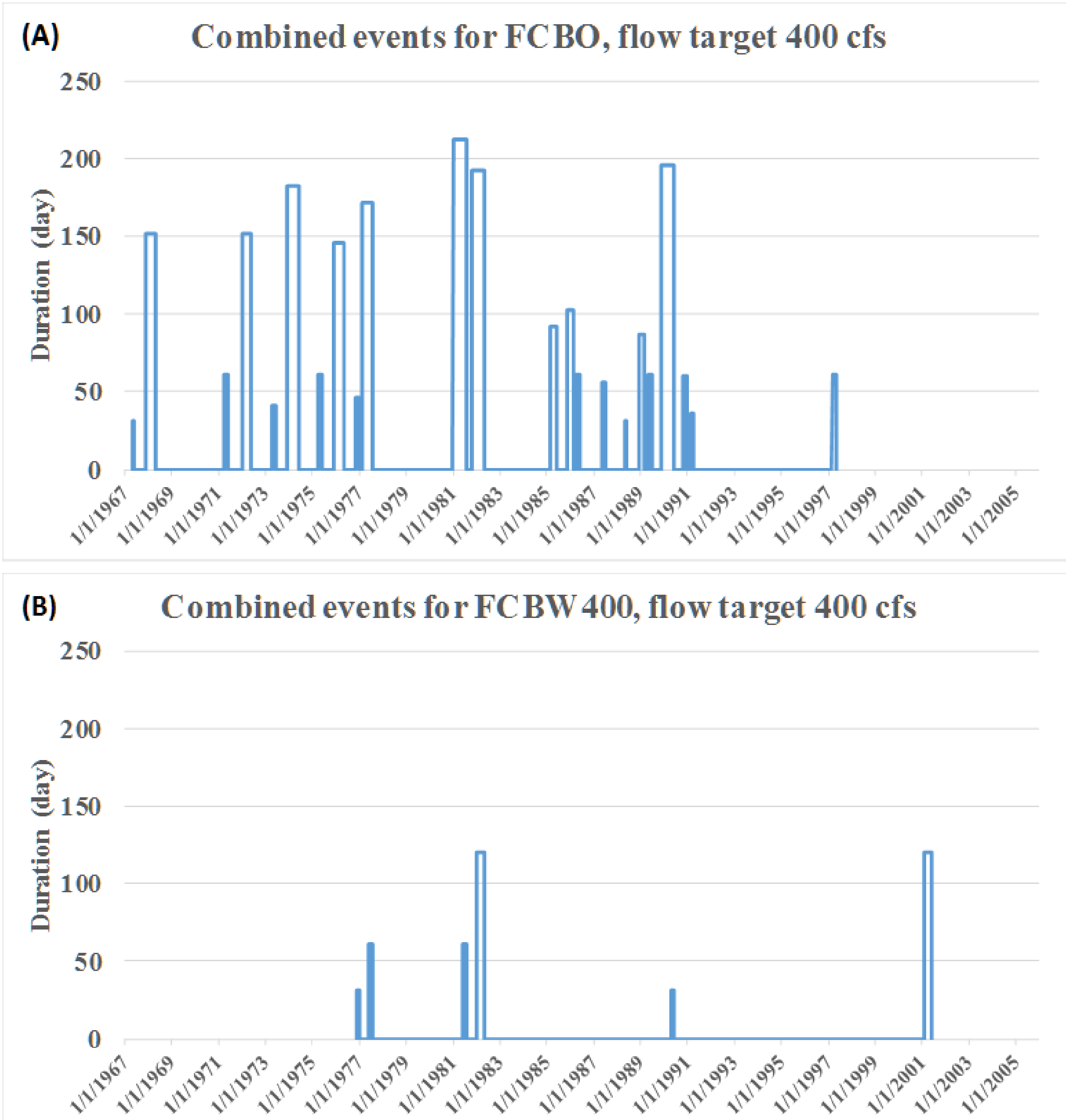


Figure 54. Combined flow exceedances and high salinity events for (A) FCBO and (B) FCBW400 with a flow target flow of 400 cfs. (Note: The location of each bar indicates the timing of the events, the number of the bars indicates the number of events, and the height of the bar indicates the duration of each event.)

There would be 23 or 24 combined flow exceedance and high salinity events during the POR if there is no reservoir for the ECB runs (**Table 17** and **Figures 51A** and **53A**). The number of combined events would be reduced to 3 with the reservoir and a flow target of 300 cfs (**Figure 51B**). There would be a total of 5 combined events if the flow target is raised to 400 cfs (**Figure 53B**). For the future hydrological condition, the number of combined flow exceedance and high salinity events without the reservoir would be 22 with a flow target of 300 cfs and 23 if the flow target is 400 cfs. The number of combined events would be reduced to 4 with the reservoir and a 300-cfs flow target or 6 if the flow target is 400 cfs.

Conclusion

The scenario simulations using the CH3D CRE Hydrodynamic/Salinity Model suggest that introduction of the reservoir would significantly reduce salinity at the Ft. Myers and Val I-75 monitoring stations (**Figures 49** and **50**). The number of high salinity events, defined as salinity greater than 10 for 55 or more consecutive days at Ft. Myers, are not significantly reduced, in part, because the longer duration events are broken down into smaller events that occur more frequently (**Table 16**). However, the average duration and average salinity are significantly reduced at the Ft. Myers station. The C-43 Reservoir is projected to bring the number of combined events (flow and high salinity) down significantly from the middle twenties to low single digit (**Table 17** and **Figure 51**). With a target flow of 300 cfs, the combined exceedance events (flow and salinity) without and with the C-43 Reservoir are provided for the existing (**Figure 51**) and future conditions (**Figure 52**). The model results show there is no significant difference between a 300-cfs flow target or a 400-cfs flow target.

EVALUATION OF IMPACT FROM SEA LEVEL RISE

The impact on salinity from SLR was evaluated by performing sensitivity tests of SLR using the CH3D CRE Hydrodynamic/Salinity Model (see Component 1, **Appendix A**). The first test was based on a SLR of 3 millimeter per year (mm/yr) in the next 20 year (or planning period). In 20 years, the mean sea level was projected to be 6 centimeters (cm) higher than the existing condition. This projected rate was based on the statistics of observed water level at the Ft. Myers station by the National Oceanic and Atmospheric Administration (**Figure 55**).

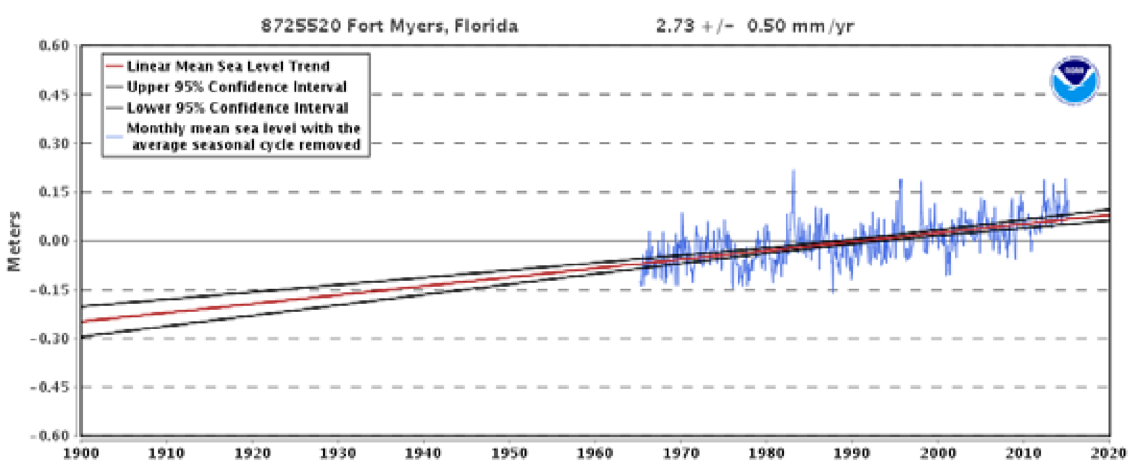


Figure 55. Sea level trend at the Ft. Myers station, which is National Oceanic and Atmospheric Administration station 8725520, showing an increase of 2.73 mm/yr.

To simulate this hypothetical scenario, tidal level at the ocean boundary was increased by a constant of 0.06 m from the existing condition for a simulation period from 2001 to 2010. The other boundary conditions such as freshwater inflow and meteorological forcing were the same as the existing condition. **Figure 56** shows the modeled surface salinity at the Ft. Myers station compared with the existing condition. The difference between the existing condition and this SLR scenario is barely noticeable.

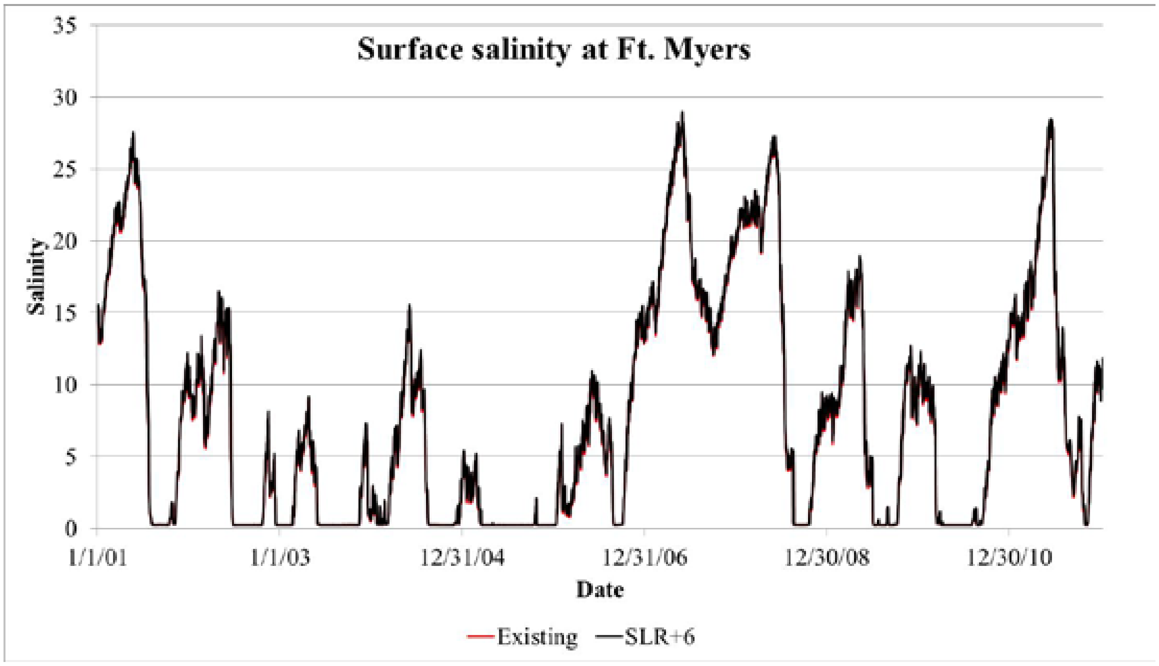


Figure 56. Surface salinity at the Ft. Myers station with a SLR of 6 cm (SLR+6) compared with the ECB (Existing).

Further sensitivity tests were performed assuming SLR from 5 to 20 cm from the ECB. Model results (**Figure 57**), suggested insignificant salinity changes at the Ft. Myers station if SLR is less than 10 cm. However, with a SLR 15 to 20 cm, peak salinity at dry season would increase by 2 to 3 points at the Ft. Myers station. **Figure 57** shows the predicted average salinity change in the month of May 2007, during a severe drought event, in response to SLR.

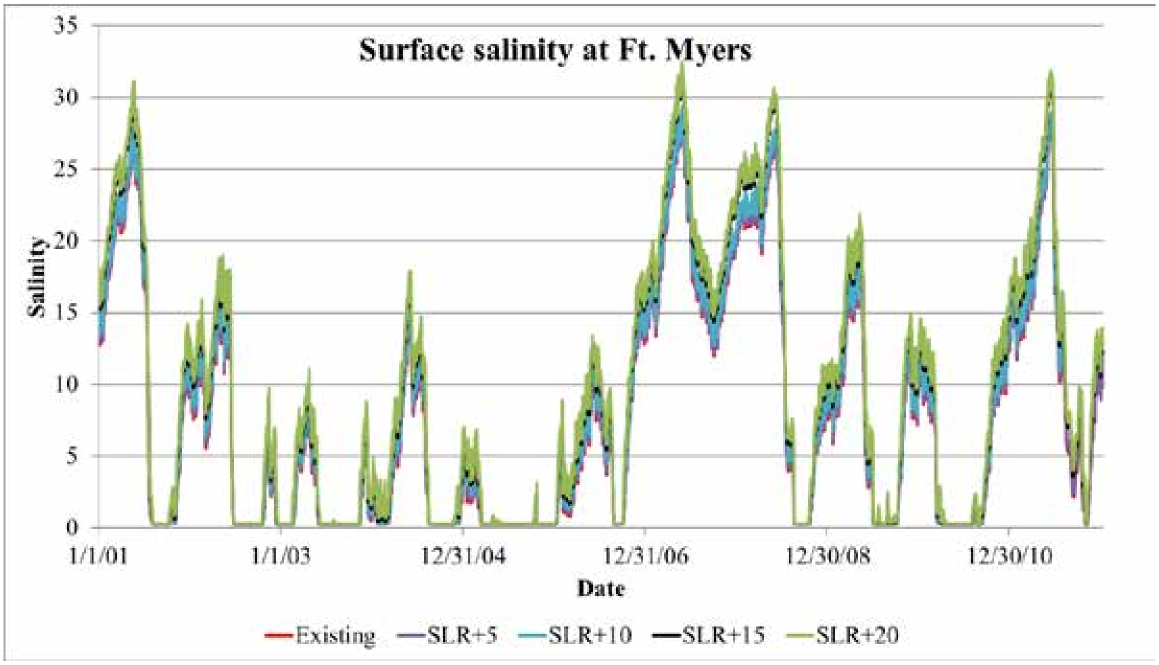


Figure 57. Sensitivity tests showing modeled surface salinity at the Ft. Myers station with sea level difference from 5 to 20 cm compared with the ECB (Existing). (Note: SLR+5 - sea level rise of 5 cm; SLR+10 - sea level rise of 10 cm; SLR+15 - sea level rise of 15 cm; and SLR+20 - sea level rise of 20 cm.)

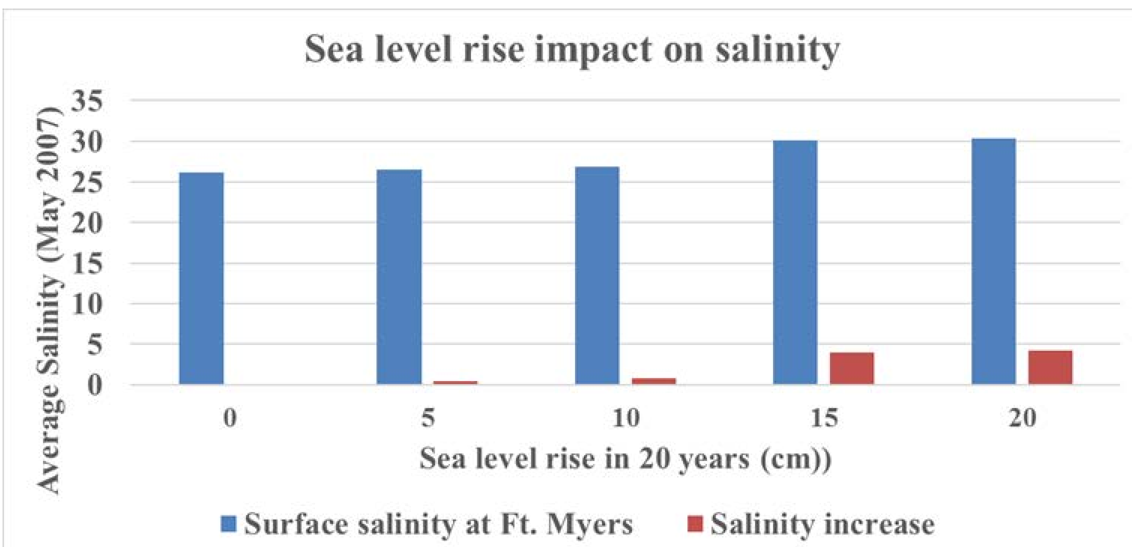


Figure 58. Average salinity in May 2007 in response to SLR.

EVALUATION OF EFFECTS OF STRUCTURAL ALTERATIONS ON SALINITY WITHIN THE CRE

The last application of the CH3D CRE Hydrodynamic/Salinity Model was used to perform five model tests on physical alterations in the CRE and compared with the ECB. The physical alterations evaluated were the (1) removal of the S-79 water control structure; (2) removal of the downstream causeway (Sanibel); (3) backfill of the oyster bar near the estuary mouth; (4) backfill of the navigation channel; and (5) reestablishment of predevelopment bathymetry. Model results indicated that refilling the navigation channel had profound effects with a 20% reduction in dry season salinity (**Figure 59**).

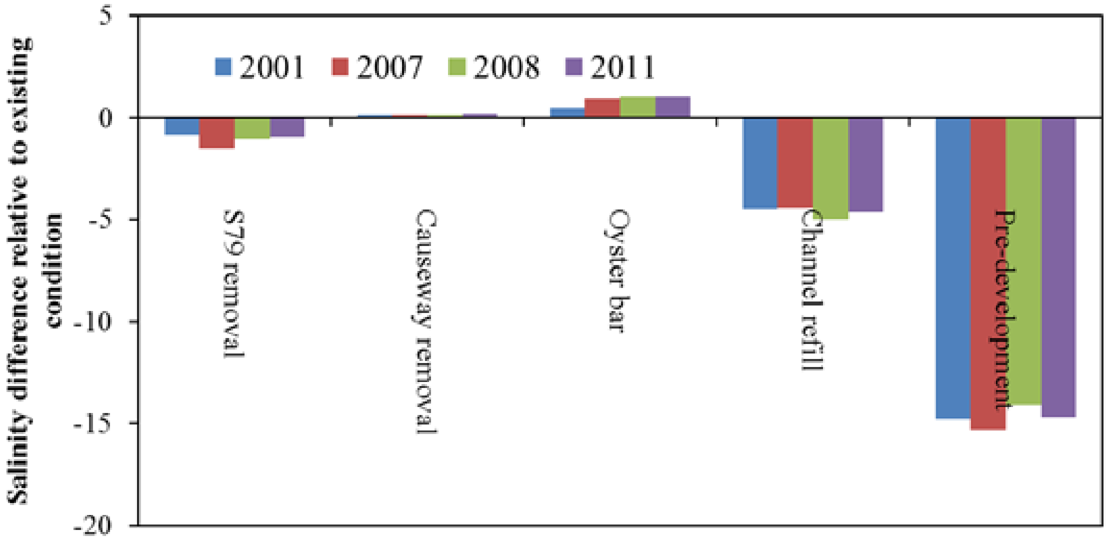


Figure 59. Monthly mean salinity differences at the Ft. Myers station relative to ECB in May 2001, 2007, 2008, and 2011 for five physical alteration scenarios.

Tape Grass Model

In 2003, a numerical model was constructed to integrate relevant information and predict the growth and survival of *Vallisneria americana* Michx. (tapegrass, wild celery) in the upper CRE. This model was produced in response to peer review recommendations (Edwards et al. 2000). The model includes growth responses relative to salinity, light, and temperature (SFWMD 2003). In this initial model version, growth relationships for salinity were based on field data and experimental mesocosm studies using *Vallisneria* from the Upper CRE. The model can simulate growth of *Vallisneria* at two stations in the protected area of the estuary.

Subsequent to 2003, the initial calibration conditions of regrowth were monitored after extirpation of *Vallisneria* in the Upper CRE due to drought conditions in 2001. This new data allowed for calibration and verification during a multi-year reestablishment period, represented as Model Version Val-2. Evaluations using Val-2 showed the importance of the parameters used in the temperature growth relationship, and representation of acute environmental tolerances for all three variables.

Experimental mesocosm work using *Vallisneria* from the CRE was initiated subsequent to 2003 and used to formulate site-specific light relationships. Additionally, new field data were available, allowing for model enhancements and expanded applications. Based on these updated data, the model was restructured (see Component 8 in **Appendix A**) with integration of new temperature data and site-specific light relationships related to freshwater inflows in the Upper CRE (Bartelson et al. 2014). The new model is calibrated with over 10 years of data covering a wide range of environmental conditions.

The model to simulate changes in the shoot biomass of *Vallisneria americana* (V_{shoot}; grams dry weight per square meter [gdw m^{-2}]) developed in Component 8 (**Appendix A**) was modified to evaluate potential benefits provided by the installation and operation of the C-43 Reservoir. It was designed to be part of an integrative modeling framework that links freshwater inflows, estuarine hydrodynamics and salinity distributions, and resources such as *Vallisneria* habitat in the Upper CRE (**Figure 60**). A similar approach was used to predict changes in seagrass and oyster densities in the CRE and the St. Lucie Estuary with alternative freshwater discharges associated with the Central Everglades Planning Project (CEPP; Buzzelli et al. 2015).

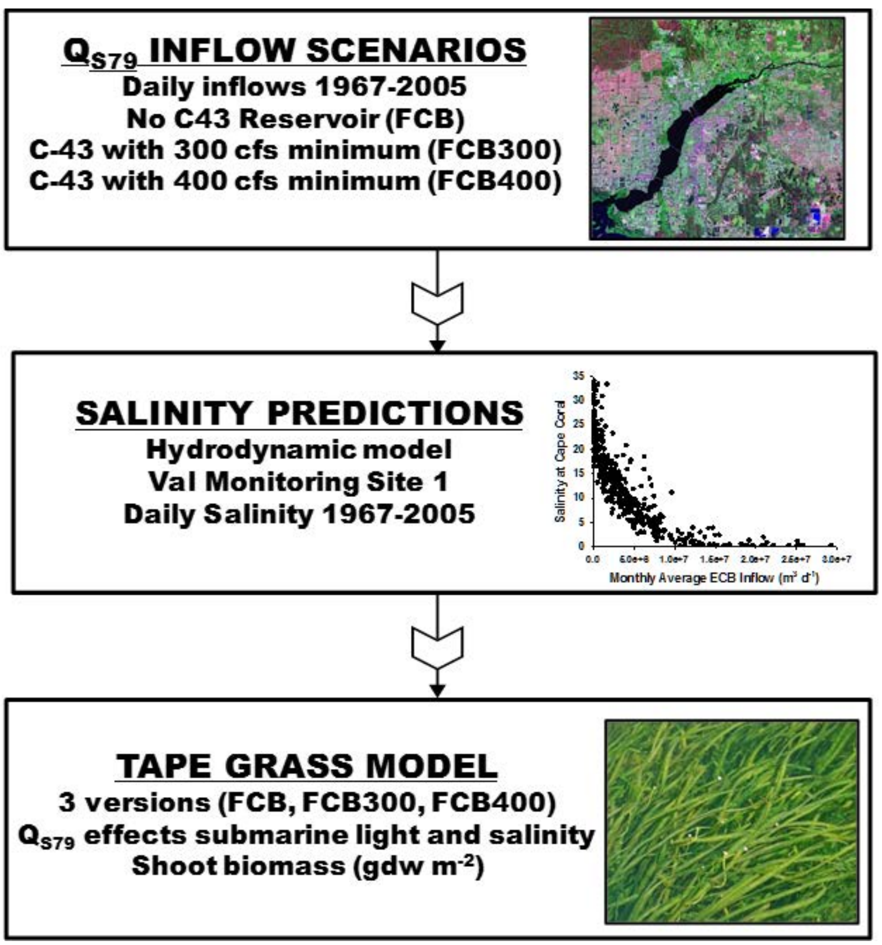


Figure 60. Schematic illustrating the integrative modeling framework used to connect S-79 freshwater inflow scenarios, estuarine hydrodynamics, and biotic resources such as *Vallisneria* (tape grass) habitat in the Upper CRE.
(Note: $m^3\ d^{-1}$ – cubic meters per day.)

This estuarine ecological modeling component focused on the future conditions inflow scenarios, which included considerations for future land and water use. Three separate daily freshwater inflow scenarios were applied from January 1, 1967, to December 31, 2005. The first was the FCB, which did not include the C-43 Reservoir. The other two inflow scenarios added installation and operation of the reservoir but with minimum inflow rates through S-79 of 300 cfs (FCB300) and 400 cfs (FCB400). The CH3D Model was used to predict daily salinity values at SAV Monitoring Site 1 (S_{site1}) in the Upper CRE from January 1, 1967, to December 31, 2005, for each of the three inflow scenarios (FCB, FCB300, and FCB400). This is the same location for which the Tape Grass Model was developed.

Since the initial Tape Grass Model was based on information collected from 1997 to 2014, the submarine light component had to be modified for the long-term simulation of shoot biomass. Long-term water column conditions are hindered by the overall lack of estuarine water quality data prior to the 1990s for the CRE. The modeling approach introduced both daily variations and intraannual (e.g. seasonal) signals for chlorophyll *a* and turbidity, but not interannual or long-term variations. Monthly average chlorophyll *a* and turbidity at station CES04 in the upper CRE from 1999 to 2015 were interpolated to produce daily values and a standard 365-day year. The standard year of daily chlorophyll *a* and turbidity were repeated to span the entire 39-year simulation time. This approach is possible because most of the light attenuation is due to colored dissolved organic matter, which is included in freshwater inflow (Bowers and Brett 2008). This is an important feature of the CRE, as inflow influences gradients of both salinity and water clarity (Buzzelli et al. 2014b, c, Chen et al. 2015).

Daily inflow rates through the S-79 structure were transformed into a partial light attenuation coefficient for color in the Upper CRE (k_{color}). Two independent linear regression equations accounted for the effects of color on submarine light attenuation (**Figure 61**). First, inflow at S-79 (Q_{S79}) was used to predict color in the CRE (**Figure 61A**; Chen et al. 2015). Second, the predicted color was used to estimate k_{color} (**Figure 61B**: McPherson and Miller 1987). This light extinction factor was combined with that due to chlorophyll *a* (k_{chl}) and turbidity (k_{turb}) to estimate the total light attenuation coefficient (K_t; Buzzelli et al. 2012). K_t provided a dependent variable with which to evaluate the alternative inflow scenarios. The model formulation resulted in a robust linear relationship between the inflow rate at S-79 and the total submarine light attenuation coefficient in the Upper CRE (**Figure 61C**).

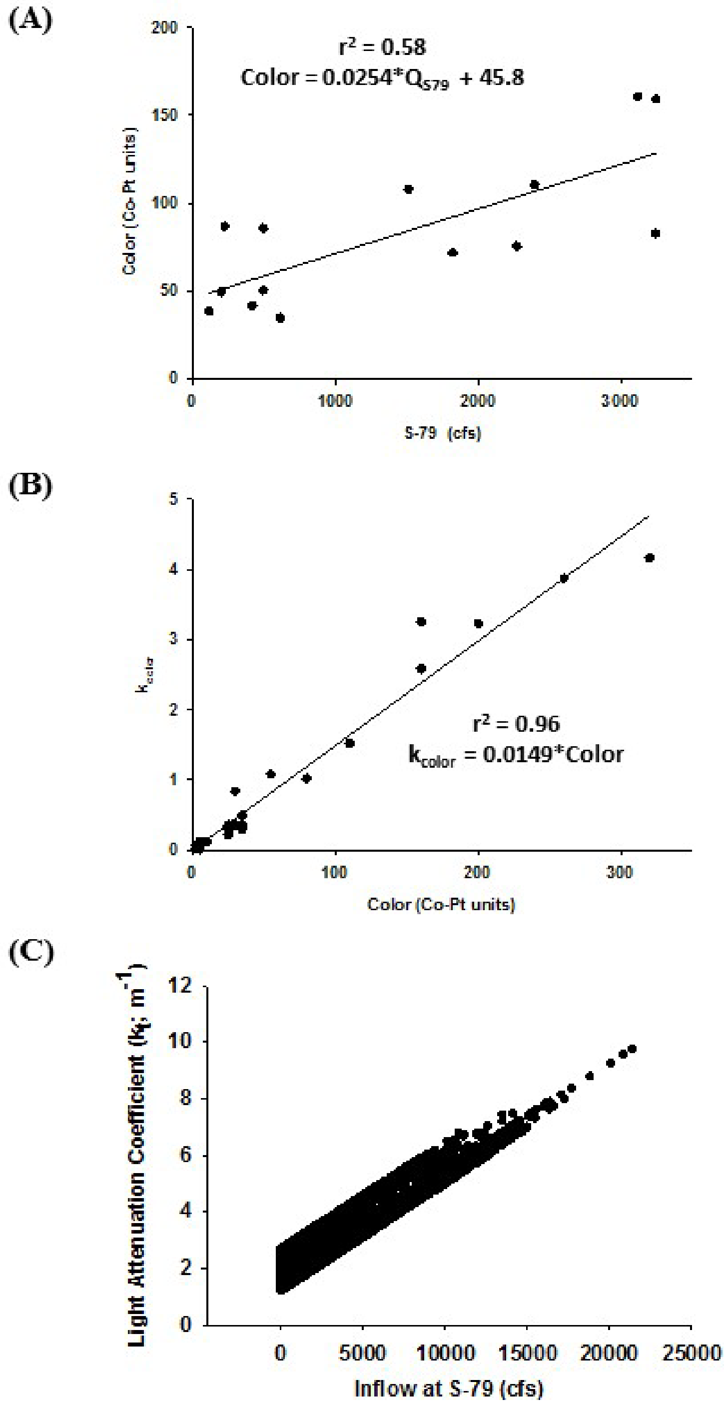


Figure 61. (A) Linear regression between the inflow rate at S-79 and the color (cobalt-platinum [Co-Pt] units) of the CRE (from Chen et al. 2015). (B) Linear regression between estuarine color and the partial submarine light attenuation coefficient (k_t; from McPherson and Miller 1987). (C) Scatterplot between the inflow rate at S-79 and the total submarine light attenuation coefficient from daily model output.

Descriptive statistics (range, average, and standard deviation) were performed on the daily values of Q_{S79}, salinity at Site 1 (S_{site1}), K_t, and V_{shoot} from January 1, 1967, to December 31, 2005. Average monthly values were plotted over time (sample size = 468), and, used in two-way analysis of variance (ANOVA) model to assess the effects of season (dry versus wet) and inflow scenario (FCB, FCB300, and FCB400). This MFL research has established that *Vallisneria* could incur significant harm if salinity was ³ 10 for > 55 consecutive days (see **Chapter 6**). This occurrence was defined as a high salinity event and applied as a final metric with which to contrast the three inflow scenarios.

Q_{S79} averaged 1,550 ± 2,150 cfs, 1,536 ± 1996 cfs, and 1,537 ± 1991 cfs among the FCB, FCB300, and FCB400 inflow scenarios, respectively (**Table 18**). These differences were manifested in differences in predicted salinities as salinity ranged from 0.2 to 34.4 and averaged 5.6 ± 7.3 in the FCB scenario without the C-43 Reservoir. The maximum and average salinities decreased to 25 and 3.6 with the introduction of the reservoir under the FCB300 and FCB400 inflow scenarios, respectively. As expected, due to the importance of color in submarine light attenuation, K_t followed Q_{S79} throughout the 39-year period and averaged 2.3 per meter (m^{-1}) for all three inflow scenarios. While the reservoir did not influence submarine light in the Upper CRE, there were important impacts on *Vallisneria* as the simulated shoot biomass (V_{shoot}) increased from 16.2 to ~20.0 grams dry weight per square meter (gdw m^{-2}) between the FCB and FCB300 or FCB400 inflow scenarios (**Table 18**).

Table 18. Summary of the range and average ± standard deviation for the inflow rate at S-79 (Q_{S79}), salinity at SAV Monitoring Site 1 (S_{site1}), total light attenuation coefficient (K_t), and *Vallisneria americana* shoot biomass (V_{shoot}) for each of the three inflow scenarios from January 1, 1967, to December 31, 2005.

Condition	Q_{S79} (cfs)		$S_{Site\ 1}$		K_t (m^{-1})		V_{shoot} (gdw m^{-2})	
	Range	Average ± SD	Range	Average ± SD	Range	Average ± SD	Range	Average ± SD
FCB	5–21,182	1,150 ± 2,150	0.2–34.4	5.6 ± 7.3	1.2–9.7	2.3 ± 0.9	1.0–40.1	16.2 ± 11.8
FCB300	4–22,173	1,536 ± 1,996	0.2–24.8	3.6 ± 4.1	1.3–10.1	2.3 ± 0.8	1.0–40.1	19.9 ± 12.0
FCB400	4–21,669	1,537 ± 1,991	0.2–25.2	3.6 ± 4.0	1.3–9.9	2.3 ± 0.8	1.0–40.1	20.1 ± 11.9

The two-way ANOVA indicated that Q_{S79} varied seasonally but not by inflow scenario over the 468 months of simulation time (**Figure 62A**). However, S_{site1} was significantly different between the dry and wet seasons, and among the three inflow scenarios (**Figure 62B**). Season and scenario did not interact. While the FCB salinities were significantly different, those from the FCB300 and FCB400 were statistically similar. Average salinity values decreased by approximately 37 and 34% in the dry and wet seasons, respectively, with the inclusion of the C-43 Reservoir. While slight seasonal differences in K_t were observed, inflow scenario had no effect on the averages (**Figure 62C**). Finally, the positive influence of the reservoir in the FCB300 and FCB400 scenarios led to increased V_{shoot} although there was no quantifiable seasonal differences in average values. Compared to the FCB scenario, V_{shoot} increased by 18.6 to 19.5% (dry) and 27.4 to 28.5% (wet) as the FCB300 and FCB400 inflow scenarios included the reservoir (**Figure 62D**).

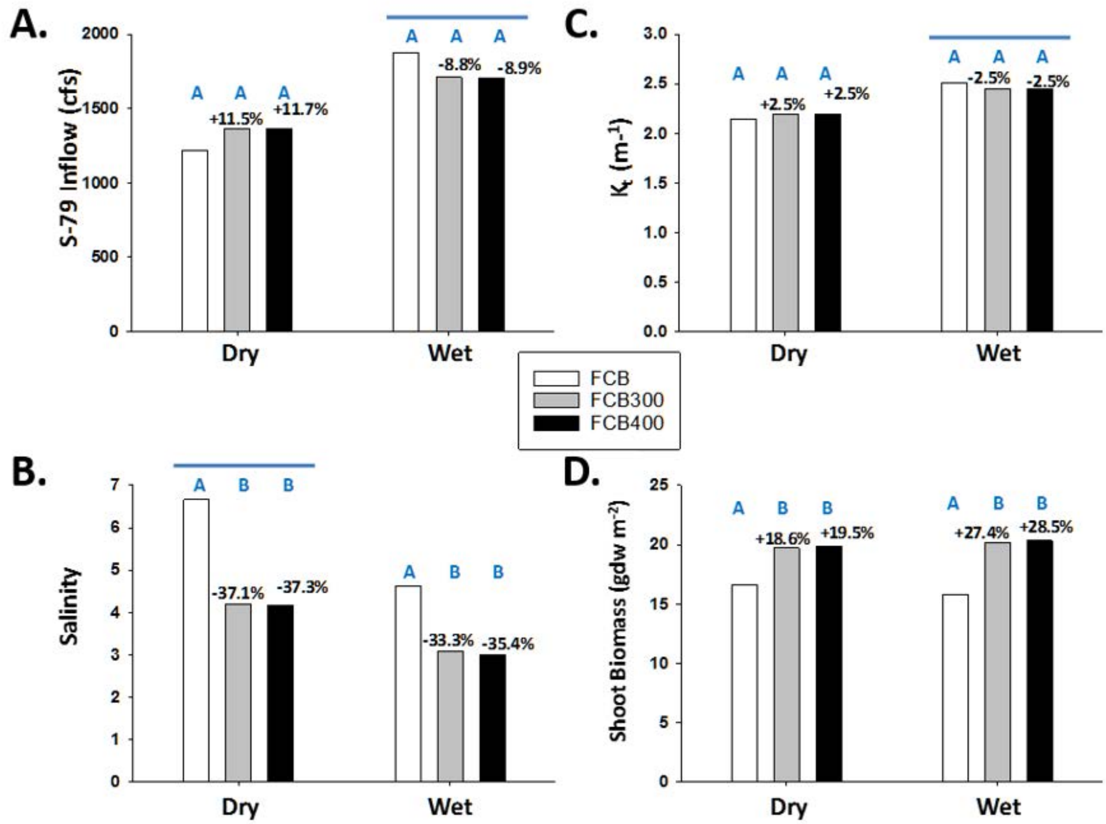


Figure 62. Results of two-way ANOVA to assess the effects of season (dry versus wet) and inflow scenario (FCB, FCB300, and FCB400) on the average (A) S-79 inflow rate, (B) salinity at SAV Monitoring Site 1, (C) total light attenuation coefficient (K_t), and (D) simulated *Vallisneria* shoot biomass at SAV Monitoring Site 1 in the Upper CRE from January 1, 1967, to December 31, 2005.
(Notes: The horizontal bar indicates statistical similarity between dry and wet seasons. The letters [A and B] indicate statistical similarity among inflow scenarios. There were no interactions between season and scenario for any of the four dependent variables.)

There were obvious intra- and interannual variations in $S_{Site\ 1}$, K_t, and V_{shoot} within and among the three inflow scenarios (**Figures 63** through **65**). Both the FCB300 and FCB400 inflow scenarios led to reduced salinity and increased V_{shoot} in the Upper CRE. In fact, the frequency, duration, and severity of high salinity events were considerably less with the inclusion of the C-43 Reservoir under these two management scenarios (**Table 19**).

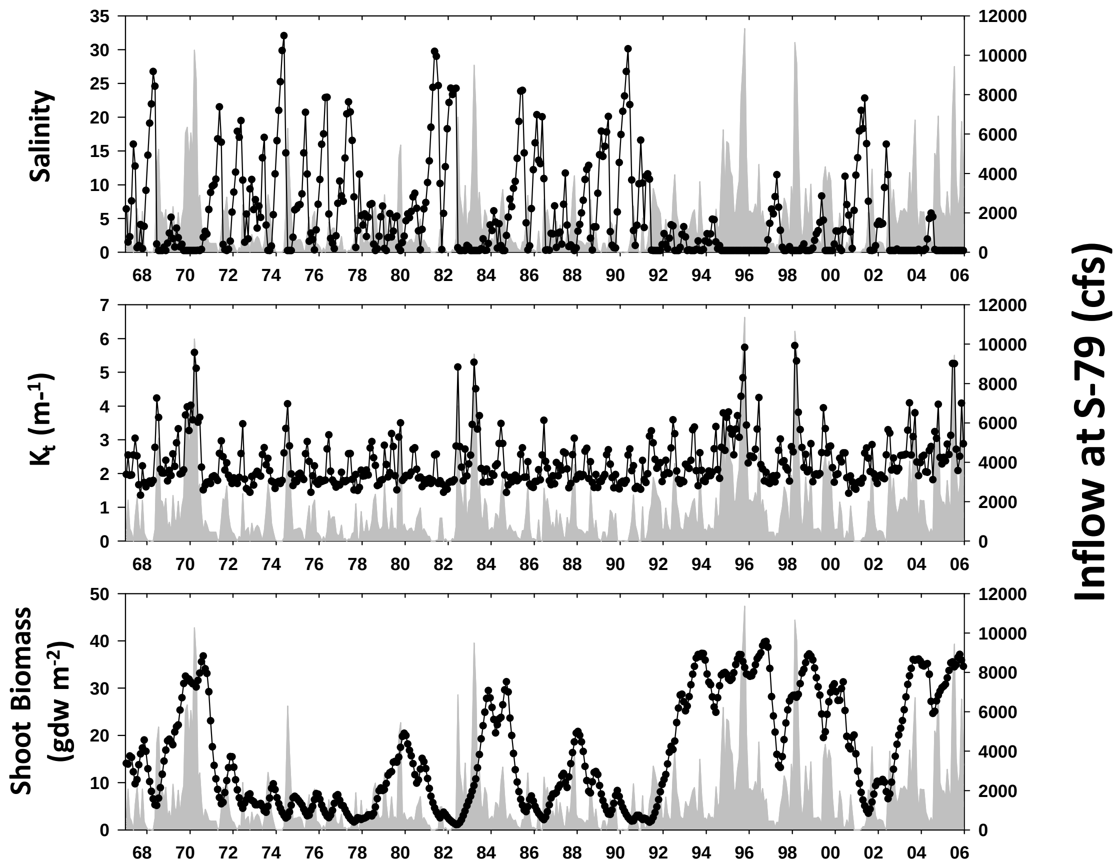


Figure 63. Long-term simulation model results predicted at SAV Monitoring Site 1 in the Upper CRE from January 1, 1967, to December 31, 2005, with time series of the average monthly salinity (top), total light attenuation coefficient (K_t; middle), and *Vallisneria* shoot biomass (bottom).
(Notes: Results are derived from the FCB inflow scenario, which included considerations for future land and water use but not the C-43 Reservoir. See the text for details.)

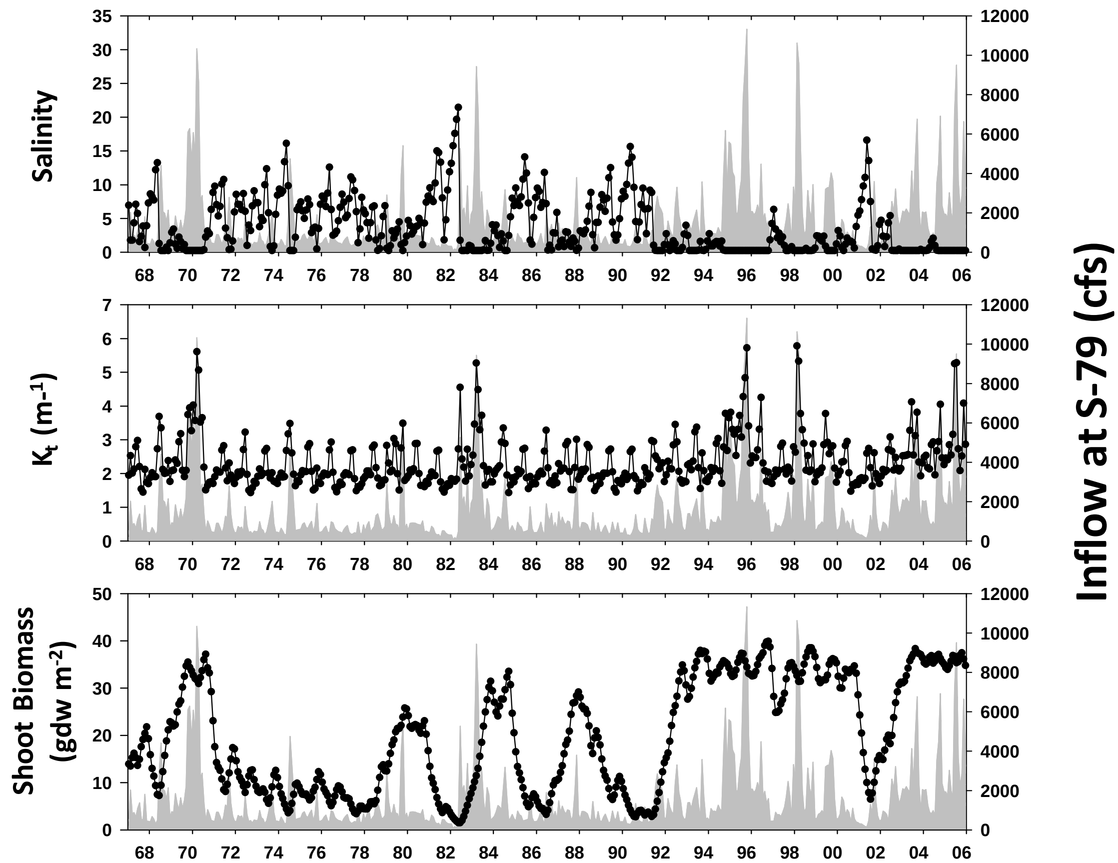


Figure 64. Long-term simulation model results predicted at SAV Monitoring Site 1 in the Upper CRE from January 1, 1967, to December 31, 2005 with time series of the average monthly salinity (top), total light attenuation coefficient (K_t; middle), and *Vallisneria* shoot biomass (bottom).
(Notes: Results derived from the FCB300 inflow scenario, which included considerations for future land and water use and the C-43 Reservoir with a 300-cfs minimum inflow rate at the S-79 structure.
See the text for details.)

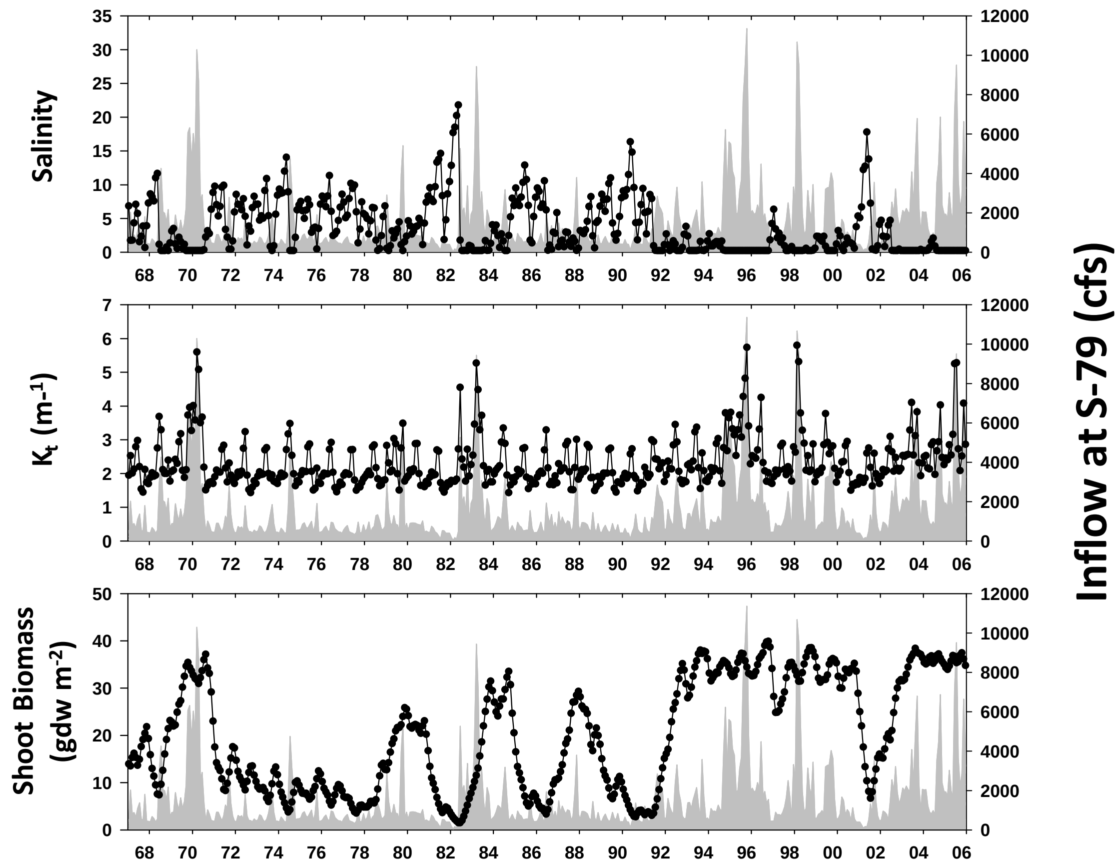


Figure 65. Long-term simulation model results predicted at SAV Monitoring Site 1 in the Upper CRE from January 1, 1967, to December 31, 2005, with time series of average monthly salinity (top), total light attenuation coefficient (K_t; middle), and *Vallisneria* shoot biomass (bottom). (Notes: Results derived from the FCB400 inflow scenario, which included considerations for future land and water use and the C-43 Reservoir with a 400-cfs minimum inflow rate at the S-79 structure. See the text for details.)

Table 19. Tabulation of high salinity events at SAV Monitoring Site 1 in the Upper CRE from January 1, 1967, to December 31, 2005, under the three different inflow scenarios (FCB, FCB300, and FCB400). (Notes: A high salinity event was defined as those where $S_{site1} \geq 10$ for ≥ 55 consecutive days. See **Chapter 7** for details.)

Scenario	Number of Events	Duration (days)	Salinity	Percent *Vallisneria* Shoots Lost
FCB	20	137	17.7	57.7
FCB300	8	100	13.6	48.5
FCB400	6	115	13.8	54.1

The number of events where S_{site1} was ³ 10 for ³ 55 days decreased under the FCB (20 events), FCB300 (8 events), and FCB400 (6 events) inflow scenarios. While the average duration and salinity were 137 days and 17.7 under FCB, these values were 100 days and 13.6 with FCB300, and 115 days and 13.8 with FCB400 (**Table 19**). An average of almost 58% of the V_{shoot} were lost during each high salinity event without the C-43 Reservoir. This value improved to 48.5–54.1% for the FCB300 and FCB400 scenarios. While there were no statistically significant differences between FCB300 and FCB400 among the four dependent variables, there were subtle differences in the number of events, duration, and salinity. These differences were related to the operation of the reservoir given the two different minimum inflow targets (e.g. 300 versus 400 cfs). Overall, the changes in the magnitude of V_{shoot} over the 39-year simulation period were indistinguishable between the FCB300 and FCB400 inflow scenarios.

A summary of this model application to evaluate the CRE MFL recovery strategy is included in **Chapter 10**.

CHAPTER 8: EVALUATION OF RECOMMENDED MFL CRITERIA

RECOMMENDED MFL CRITERIA

Reevaluation of the existing Caloosahatchee River MFL criteria involved a comprehensive assessment of the effects of dry season freshwater inflow on the CRE (**Chapter 5** and **Appendix A**). Once the specific needs of multiple ecological indicators were evaluated along with the analysis described in **Chapter 6**, staff recommend the following MFL criteria for the CRE:

- The minimum flow is a mean monthly flow of 400 cfs measured at the S-79 structure.
- An MFL exceedance occurs during a 365-day period when the 30-day moving average flow at S-79 declines below 400 cfs and the daily average salinity at the Ft. Myers station has exceeded 10 for more than 55 consecutive days.
- An MFL violation occurs when an exceedance occurs more than once in a five-year period.

These recommended MFL criteria were analyzed using modeling tools to determine if the criteria will be met under the Existing Condition Base (ECB) and Future Condition Base (FCB) model simulations. The model simulations used for the evaluation of the recommended MFL criteria do not include the recovery strategy because the purpose of this evaluation was to determine if the minimum flow in the MFL waterbody (CRE) is below, or projected to be below, the revised recommended minimum flow criteria (Section 373.0421(2), F.S.). The end result of this evaluation will be to determine if a recovery or prevention strategy is required by Florida Statutes.

Model simulations were used to evaluate exceedance events for minimum flows, salinity, and flow and salinity together. Flow criteria were evaluated by using the mean monthly flows that are less than 400 cfs at the S-79 structure. The recommended salinity criteria were evaluated by examining the frequency and duration under which the high salinity events would occur in the middle of the estuary. A high salinity event at the Ft. Myers station is defined as salinity greater than 10 for 55 or more consecutive days. Modeling was also used to evaluate the frequency and duration when both flow (< 400 cfs) and high salinity exceedance events occurred. These three separate exceedance evaluations (flows, salinity, and flow and salinity together) were completed without the C-43 Reservoir in place.

To evaluate the recommended minimum flow criteria, the SFWMM was used to determine the total number of months when the flows were less than 400 cfs under the ECB with 2012 demands using current system operations. The model results presented in **Figure 66** show a total of 97 months when flow exceedances would occur during the 39-year POR. For comparison, the existing MFL criteria of 300 cfs was also evaluated, which showed a total of 83 months when flow exceedances would occur.

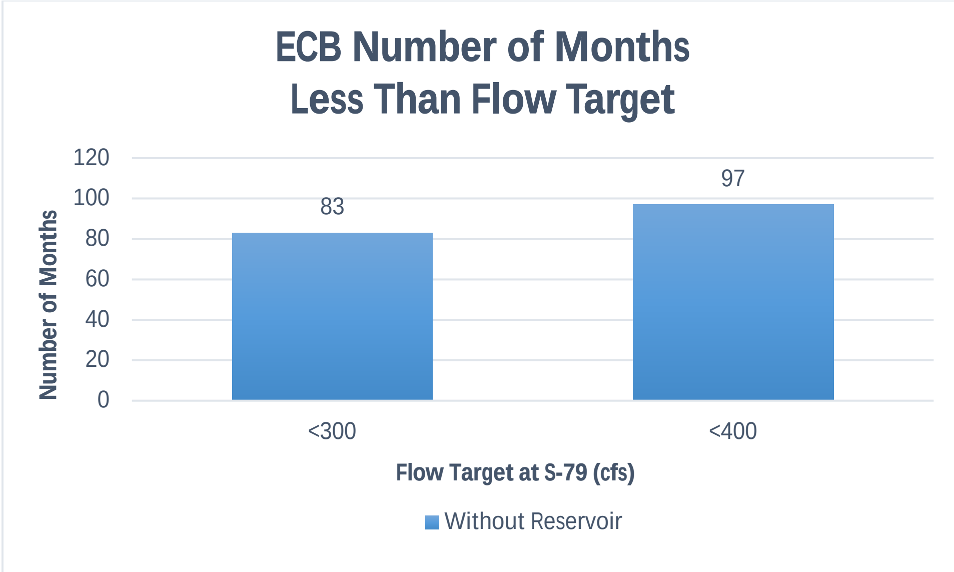


Figure 66. Number of months flow was less than the flow target for the ECB.

The FCB without project uses 2040 demands and other future CERP projects in place. Under the FCB, the model results show a total of 106 months where flow exceedances (< 400 cfs) would occur within the 39-year POR (**Figure 67**). Using the existing criteria of flows less than 300 cfs, there would be a total of 91 months where flow exceedances would occur.

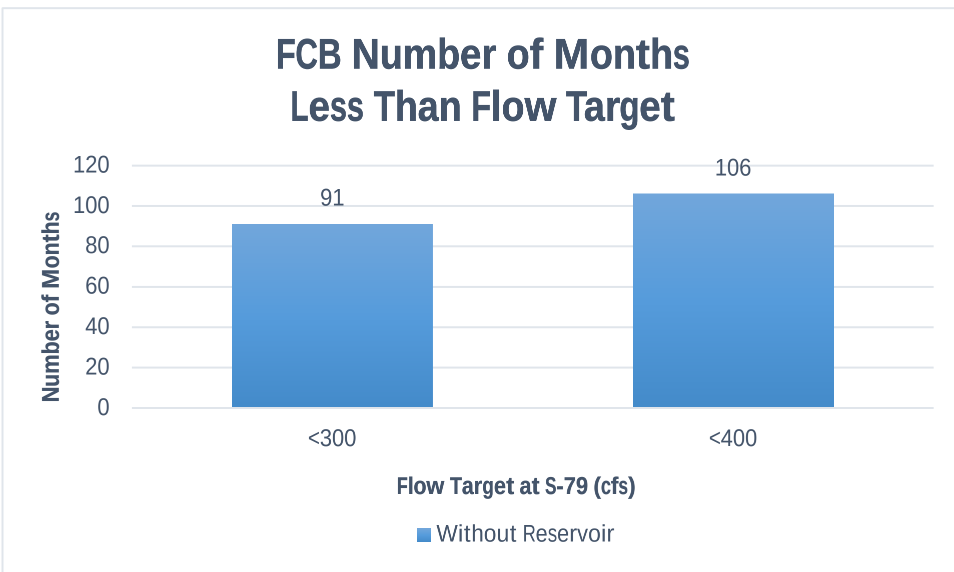


Figure 67. Number of months flow was less than the flow target for the FCB.

The salinity criteria were evaluated using the CH3D Hydrodynamic/Salinity Model to determine the frequency of high salinity events in the middle estuary. **Table 16** shows that under existing and future model scenarios (ECBO and FCBO) the number of high salinity events are expected to occur 23 and 22 times, respectively, over the 39-year POR. When flows are less than

400 cfs, there is a significant likelihood that a high salinity event would still occur during a drought event (**Table 16**).

The CH3D model was also used to evaluate both flow and salinity together. This modeling effort evaluates when both combined exceedances for both flow and high salinity events occur simultaneously during the 39-year POR. Flow exceedance events (< 400 cfs) are measured at the S-79 structure using the SFWMM while high salinity events and combined flow and high salinity events are measured at the Ft. Myers salinity station using the CH3D model. **Table 17** shows the combined flow exceedance and high salinity events would occur simultaneously 24 times under the existing condition and 23 times under the future condition.

For comparsion, the existing MFL criteria (flows less than 300 cfs) were also evaluated. Using a flow of less than 300 cfs, combined exceedance events for flow and salinity would occur 23 and 22 times under ECBO and FCBO model scenarios respectively. For more details regarding the ECBO and FCBO model simulations see **Chapter 7**.

This evaluation of exceedance events for flow, salinity, and flow and salinity together demonstrates that the minimum flow is currently below the revised recommended MFL criteria for the CRE. Therefore, a recovery strategy is required by Florida Statutes (Section 373.0421(2), F.S). An evaluation of the existing recovery strategy to determine if the MFL waterbody will be recovered using the recommended MFL criteria is discussed in **Chapter 10**.

CHAPTER 9: RESEARCH AND MONITORING

During this reevaluation, SFWMD staff relied on monitoring data and past and current research to identify technical relationships among flow, salinity, and indicator responses to understand the CREs biological resources (**Appendix A**).

The following provides a summary of current and proposed research projects and monitoring needed to refine or verify the recommended MFL criteria with a future reevaluation and fill gaps in knowledge. The following research recommendations are proposed in conjunction with the existing and future monitoring of water quality, and SAV and oyster species in the upper, middle, and lower estuary. The research projects listed below over the next few years are designed to collectively evaluate and confirm these relationships and indicator responses.

CURRENT AND FUTURE RESEARCH

Tape Grass (*Vallisneria americana*) Restoration and Seed Stock Enhancement Study

This study was designed to determine if planted *Vallisneria* spreads beyond the study sites to colonize other suitable habitat in the river both upstream and downstream either by vegetative growth or seed production. Results can inform *Vallisneria* restoration efforts after completion of the C-43 Reservoir. The study project includes 52 caged populations of *Vallisneria* distributed amongst four sites on the C-43 Canal upstream of the S-79 structure. This three-year restoration project is contracted with Johnson's Engineering and began in 2015 and is a cooperative effort between SFWMD and Lee County.

SAV Monitoring Protocol Modifications

The protocol for monitoring SAV in the CRE is being modified to gain a better understanding of its survival, growth, and persistence. The methodology used over the last eight years provides information of presence and absence, which is sufficient when determining the range extent of a species. However, this metric does not equate to a measure of biomass. Monitoring biomass of vegetation provides information relating to the ecological condition of the system. It can, for example, be related to ecosystem services such as providing habitat for fish and shellfish. Biomass is also a metric applicable for models.

The new protocol involves establishing permanent transects at locations of interest or concern and using a measure of percent cover that can be empirically converted to biomass. The method is efficient and can provide rapid assessment of changes in the biomass and species composition at each site. Additionally, as need arises, this method can be used for rapid assessment after an event of concern. The new methodology was implemented in 2017 and permanent transect monitoring will continue.

Water Quality Model Improvements

Prediction of phytoplankton blooms and associated hypoxic events in the bottom water could be improved by a more sophisticated water quality model. Currently, the Florida Department of Environmental Protection has developed a water quality model for the establishment of total maximum daily loads of nutrients in the CRE. This model is based on the Environmental Fluid Dynamic Code (EFDC) hydrodynamic and water quality model. The model may be potentially modified to provide more insight into the water quality processes and help understand how freshwater inflow affects phytoplankton blooms and hypoxia in the CRE.

MONITORING STRATEGY

Over the past several decades, SFWMD has had a robust monitoring regime at various stations within the CRE using continuous and routine sampling events. Freshwater inflows, various water quality parameters, and various indicator species have been measured or sampled at different locations and frequencies within the CRE.

Real-time Freshwater Inflow Monitoring at S-79

Daily inflows (freshwater discharges) into the CRE have been measured at the S-79 structure since 1966. The recommended MFL criterion is a mean monthly flow of 400 cfs at S-79 as the minimum flow for the CRE. The S-79 structure is the MFL compliance site and the primary control point where freshwater inflows enter the CRE from the upstream C-43 Watershed (**Figure 68**). The mean monthly flows at S-79 would continue to be monitored daily to prevent MFL flow exceedances, where possible, until the recovery strategy is completed.

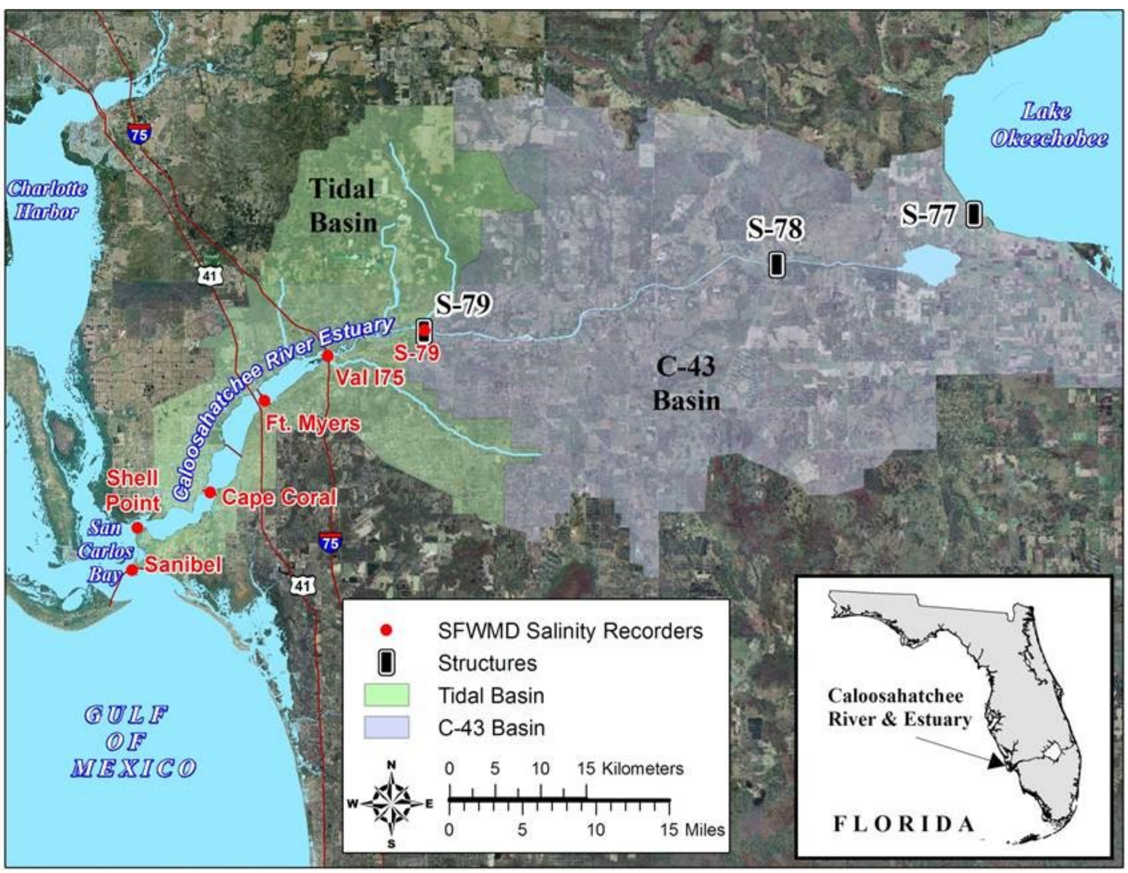


Figure 68. Location of continuous salinity recorders in the CRE (shown in red) and the continuous recorder located at S-79 to measure flows.

Real-time Salinity Monitoring

Continuous salinity monitoring will remain at the same locations in the upper, middle, and lower portions of the CRE as shown in **Figure 68**. These salinity recorders measure specific conductance and water temperature.

Estuarine Monitoring

An existing monitoring program, Surveying Estuarine Response to Freshwater Inflows (SERFIS), monitors and maps spatially contiguous water quality parameters (salinity, turbidity, chlorophyll *a* concentration, dissolved oxygen, blue-green algae, and fluorescing dissolved organic matter) and zooplankton in surface waters in the CRE. Water quality parameters are also measured vertically throughout the water column at nine fixed locations. This data provides important information that can be used to guide water management decision making of freshwater releases from the S-79 structure into the CRE. The goal of the monitoring program is to determine how best to deliver water to maximize benefits of low level releases to minimize damage from high level releases and to avoid unintended consequences (e.g. hypoxia or anoxia and algal blooms). These results and other information are also shared in the weekly operations meetings. The program was implemented in 2011 and is recommended to continue in the future.

Ecological and Water Quality Monitoring

Monitoring of two primary ecological indicators, SAV species and oysters, in the CRE will continue in the future to evaluate spatial and temporal fluctuations. Future monitoring of SAV species includes both seagrasses and *Vallisneria* at eight different monitoring sites in the upper, middle, and lower estuary (**Figure 69**). Although nine SAV monitoring sites are shown, Site 3 was discontinued in 2002 due to safety reasons. Site 6 was moved in 2012 due to the lack of SAV recruitment and oyster recolonization and renamed 6B. SAV abundance and species composition will continue to be monitored eight times a year (monthly in summer). Water quality data will continue to be monitored at nearby stations, including Secchi depth, chlorophyll *a* concentration, pH, dissolved oxygen, conductivity, salinity, and photosynthetic active radiation (stations CES04 through CES10 in **Figure 69**).

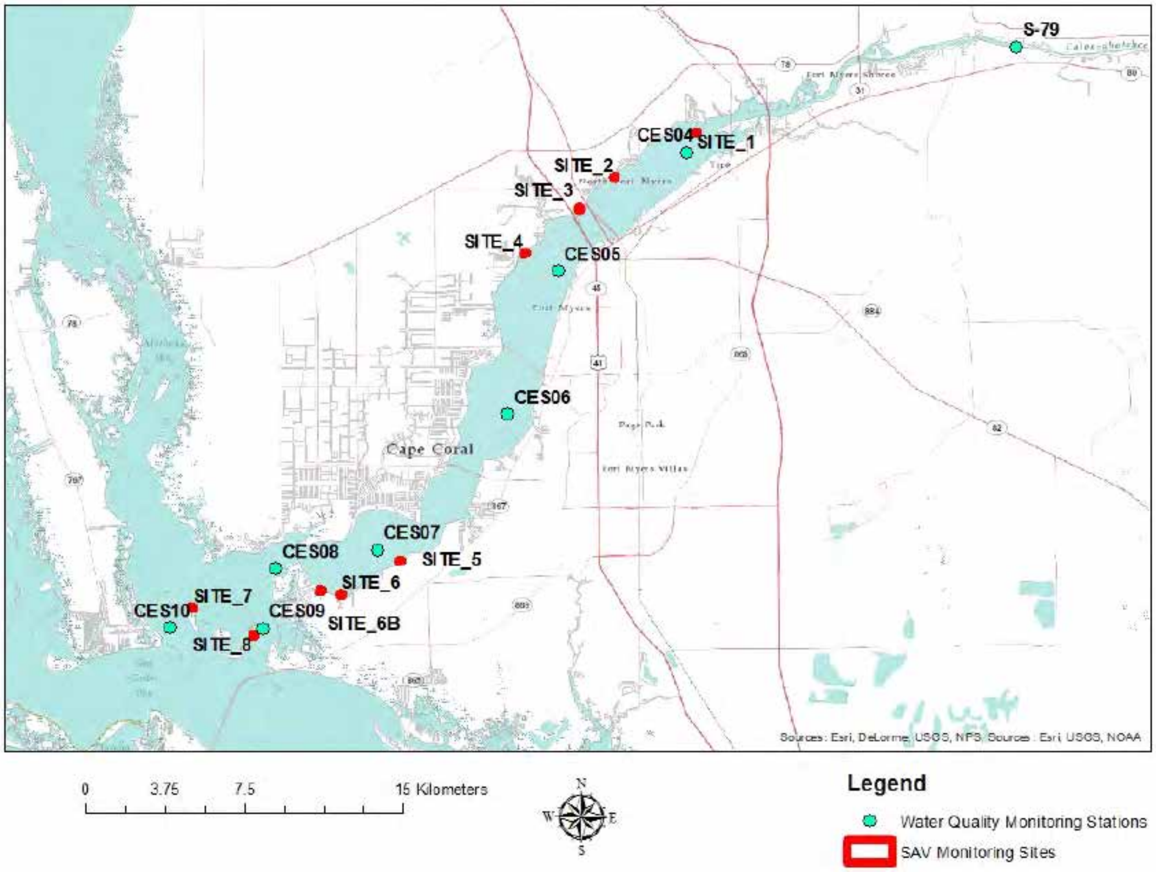


Figure 69. SAV and water quality monitoring sites in the CRE for the 1998–2013 period. (Source: RECOVER 2014.)

Basic biological information including measures of health and density of oyster ecology are currently being monitored and will continue to be monitored in the future. The different parameters collected include reproduction and recruitment, juvenile oyster growth and survival, the presence and intensity of the oyster disease *Perkinsus marinus* (dermo), and live/dead density counts of adult oysters. Monthly water quality parameters (dissolved oxygen, specific conductance, salinity, pH, and temperature) are sampled in conjunction with the field sampling at each study site (RECOVER 2014). Future oyster monitoring will continue at the four different locations in the lower CRE near the mouth of the estuary as shown in **Figure 70**. These monitoring sites include Iona Cove, Bird Island, Kitchel Key, and Pepper Tree Point (recruitment and growth only). The frequency of the monitoring will be conducted monthly except for density counts at the Iona Cove and Bird Island sites, which are done on a quarterly basis. Reports are generated quarterly with one annual report in February (**Table 20**) and a final summary report at the end of the multiyear contract.

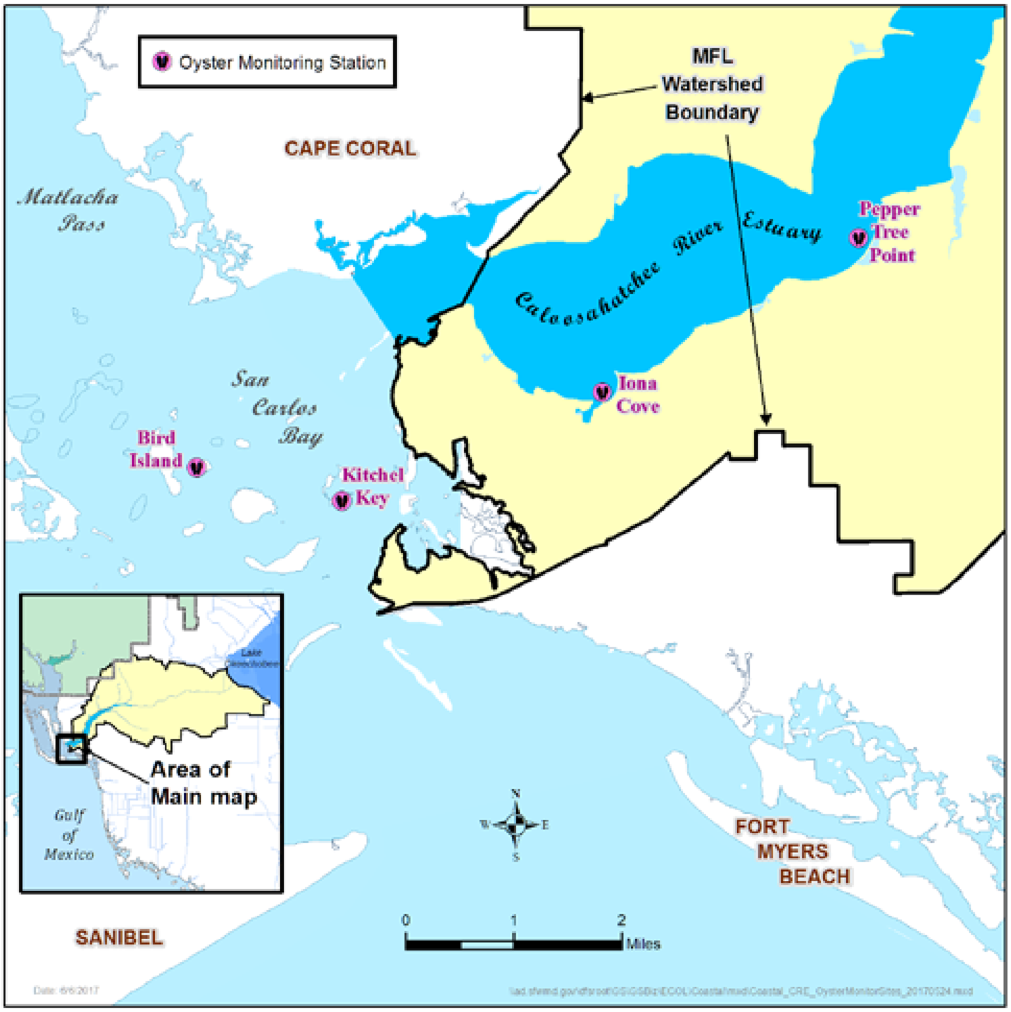


Figure 70. Oyster monitoring sites within the CRE.

Table 20. The frequency and different parameters of oyster monitoring in the CRE.

Parameter	Monthly Oyster Monitoring											
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Density Counts			X			X			X			X
Reproduction	X	X	X	X	X	X	X	X	X	X	X	X
Disease	X	X	X	X	X	X	X	X	X	X	X	X
Spat Recruitment	X	X	X	X	X	X	X	X	X	X	X	X
Growth & Survival	X	X	X	X	X	X	X	X	X	X	X	X
Water Quality	X	X	X	X	X	X	X	X	X	X	X	X
Reports a		A	Q			Q			Q			

a. A – annual and Q – quarterly.

CHAPTER 10: EXISTING RECOVERY STRATEGY AND EVALUATION

INTRODUCTION: RECOVERY AND PREVENTION STRATEGIES

Section 373.709, F.S., requires regional water supply plans to contain recovery and prevention strategies needed to achieve compliance with MFLs during the planning period. The existing recovery strategy for the CRE is identified in Appendix C of the *2017 Lower West Coast Water Supply Plan Update Appendices* (SFWMD 2017).

Section 373.0421(2), F.S., states if, at the time a minimum flow or minimum water level is initially established for a waterbody or is revised, the existing flow or water level in the waterbody is below, or is projected to fall below within 20 years, the applicable minimum flow or minimum water level, the Districts are required to concurrently adopt or modify and implement a recovery or prevention strategy. The recovery or prevention strategy shall include development of additional water supplies and other actions, consistent with the authority granted by this chapter, to:

- Achieve the recovery to the established minimum flow or minimum water level as soon as practicable; or
- Prevent the existing flow or water level from falling below the established minimum flow or minimum water level.

MFL recovery strategies are developed when the evaluation indicates MFL criteria are currently being violated (Subsection 40E-8.021(25), F.A.C.). MFL prevention strategies are developed when evaluations demonstrate the MFL criteria are not currently violated, but are projected to be violated within 20 years of the establishment of the MFL (Subsection 40E-8.021(24), F.A.C.). The recovery or prevention strategy must include both structural and non-structural actions to recover the waterbody.

The phasing or timetable for each project must be included in the strategy. Section 373.0421(2), F.S., in part, provides the following:

> The recovery or prevention strategy must include a phased-in approach or a timetable which will allow for the provision of sufficient water supplies for all existing and projected reasonable-beneficial uses, including development of additional water supplies and implementation of conservation and other efficiency measures concurrent with and, to the maximum extent practical, to offset reductions in permitted withdrawals, consistent with this chapter.

Based on the evaluation contained in **Chapter 8**, the minimum flow is currently below the proposed recommended MFL criteria (**Chapter 6**) for the CRE. Therefore, a recovery strategy is statutorily required to recover the MFL waterbody to protect the water resources within the CRE (Section 373.0421(2), F.S.).

IMPLEMENTATION PROCESS

The District recognizes that additional water is necessary within the CRE MFL watershed to meet human and environmental needs, today and in the future. The intent of the District is to meet the current and future water needs in an equitable manner by implementing its planning, capital improvement, operations, and regulatory programs. The MFL criteria for the CRE that are proposed as part of this document will be achieved through a combination of structural improvements, enhanced operational protocols, and regulatory activities.

The goal of the planning efforts is to identify the amount of water that is needed to meet present and future demands and to ensure that sufficient water is available for natural systems and consumptive uses during a 1-in-10 year drought condition. The main capital project and key component of the MFL recovery strategy is the C-43 Reservoir, which is designed to meet the future needs for the natural system. The structural components and other details of the reservoir are discussed in greater detail below.

The District has improved its operational protocols for the CRE since the MFL was adopted in 2001. Through the District's current consumptive use permitting program, groundwater and surface water resources are protected from harm. The MFL program is implemented to protect the resources from significant harm while the water shortage program is implemented to prevent serious harm to water resources (See **Figure 1** in **Chapter 1**).

EXISTING RECOVERY STRATEGY

In 2001, a recovery strategy was adopted simultaneously with the MFL rule. The adopted recovery strategy recognized that the MFL would not be achieved immediately upon rule adoption largely because of the lack of adequate regional storage, including USACE regulation schedule effects, or ineffective water drainage and distribution infrastructure. Both structural and non-structural remedies were proposed to restore the Caloosahatchee River above the MFL, through Chapter 373, F.S. authorities of the District.

The existing MFL recovery strategy, as outlined in Appendix C of the *2017 Lower West Coast Water Supply Plan Update* (SFWMD 2017), includes two main components:

- CERP Caloosahatchee River (C-43) West Basin Storage Reservoir Project.
- Water Reservation Rule for the (CERP) Caloosahatchee River (C-43) West Basin Storage Reservoir Project. This water reservation rule was adopted in 2014.

Caloosahatchee River (C-43) West Basin Storage Reservoir Project

The purpose of the Caloosahatchee River (C-43) West Basin Storage Reservoir Project (C-43 Reservoir) is to improve the quantity, timing, and distribution of freshwater flows to the CRE. Operation of the C-43 Reservoir project will capture and store surface water runoff from the C-43 Watershed and Lake Okeechobee to provide a more natural and consistent flow of fresh water to the estuary. After construction, operation of this project is expected to improve the CRE salinity balance by reducing a portion of the peak discharges during the wet season and providing essential flows during the dry season.

The recommended plan includes an aboveground reservoir located south of the C-43 Canal between the S-79 and S-78 structures on a 10,700-ac parcel west of LaBelle formerly known as Berry Groves (**Figure 71**). The reservoir will provide a total storage capacity of approximately 170,000 ac-ft of aboveground storage volume in a two-cell reservoir. Normal pool depths when the reservoir is full vary from 17 to 19 ft. Project features include external and internal embankments, canals, two pump stations, 16 internal control and outflow water control structures, and environmental features to provide fish and wildlife habitat (**Figure 72**).

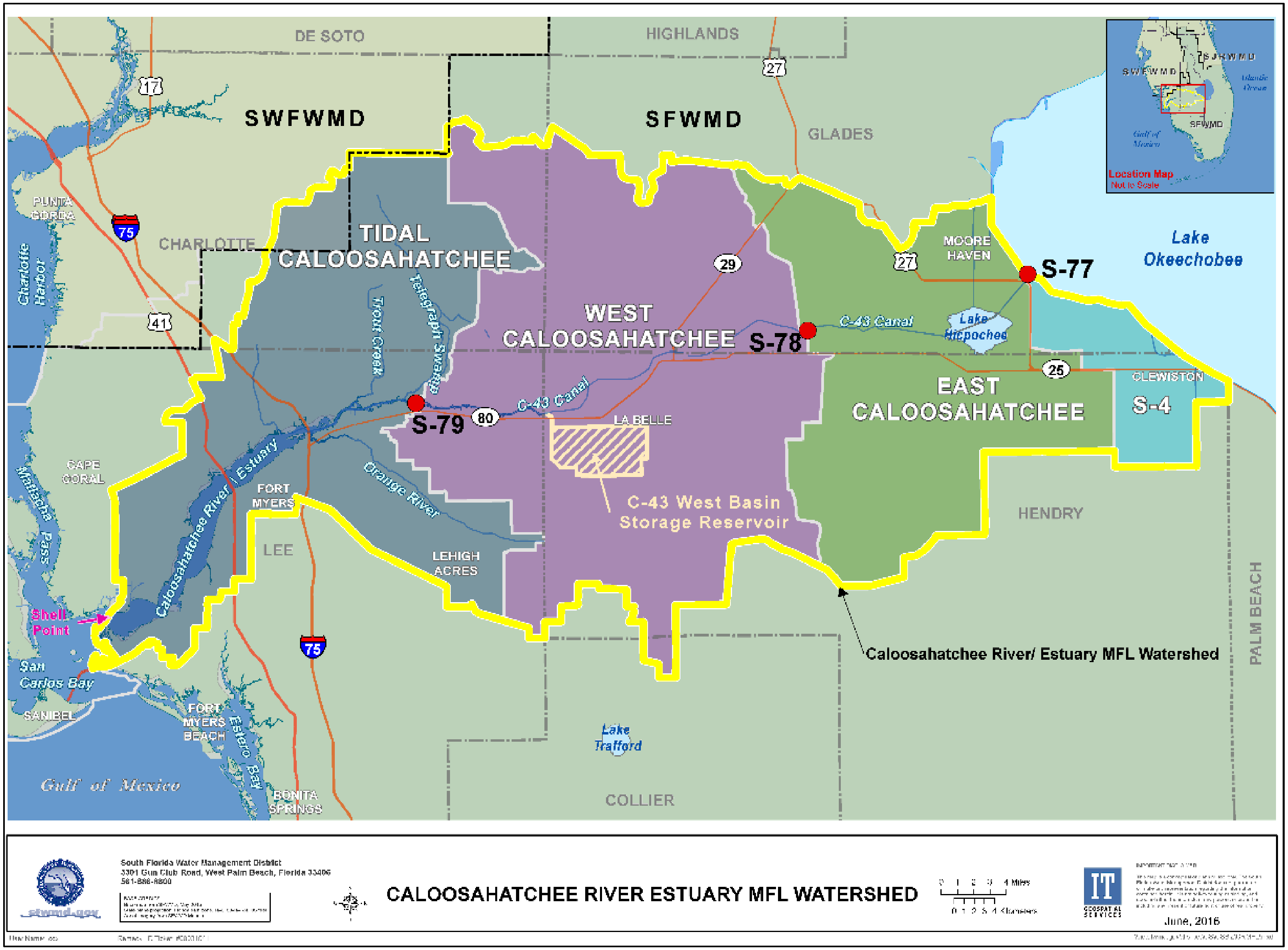


Figure 71. CRE MFL watershed showing the location of the C-43 Reservoir project.

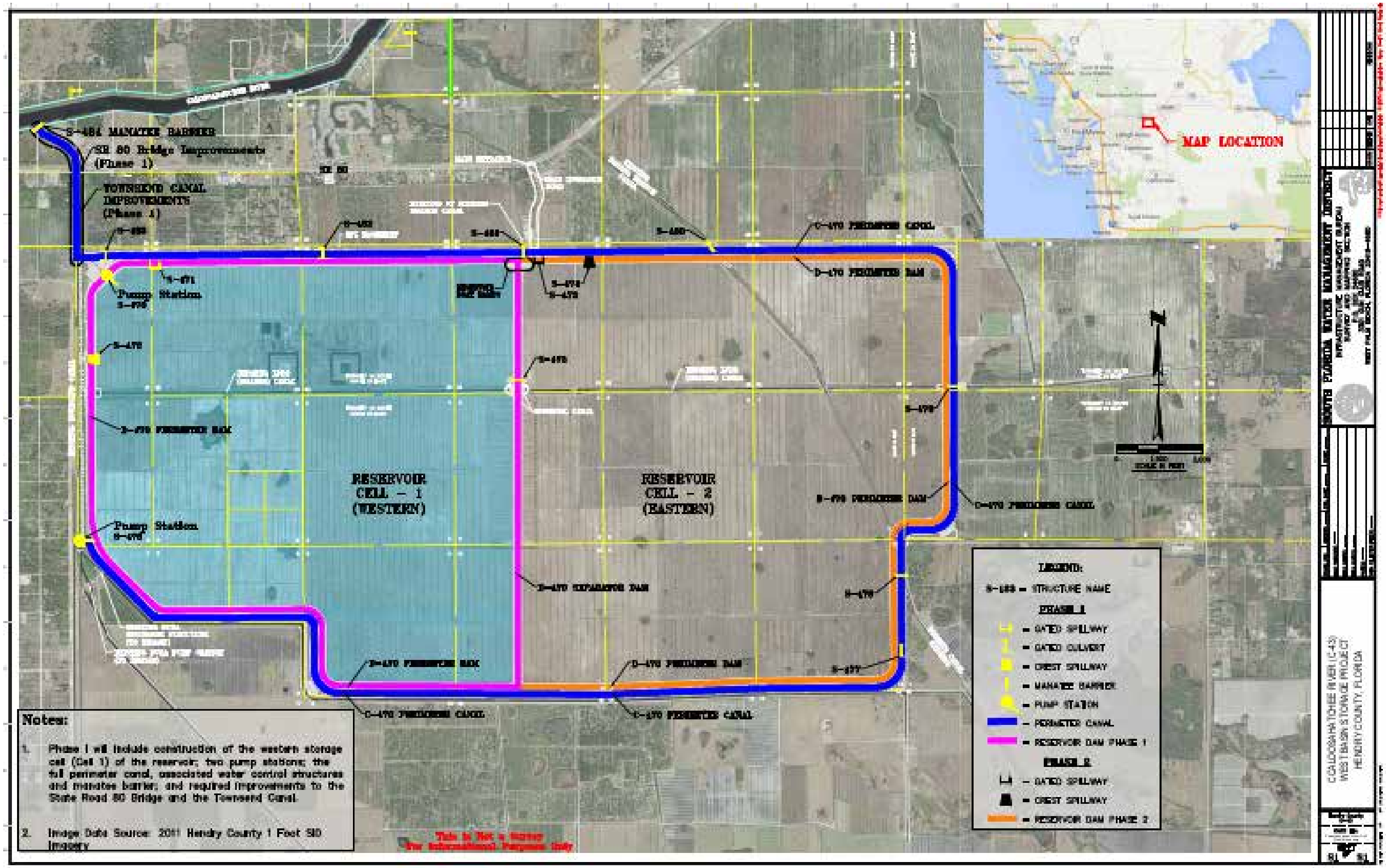


Figure 72. General site plan for the C-43 Reservoir project.

The C-43 Reservoir will be operated to improve conditions in the CRE by reducing some of the high flows through the S-79 structure during wet periods and increasing the flows during dry periods. Operations will vary based on the season, capacity in the reservoir, and salinity downstream of S-79. Once the reservoir is constructed, a detailed operational plan will be established. After the initial filling of the reservoir and operational testing and monitoring period is completed, the operational protocols are expected to be modified to improve performance of the C-43 Reservoir. The reservoir will be filled with surface water from the C-43 Canal. Water will be pumped from the C-43 Canal via the Townsend Canal into Cell 1 of the reservoir. An internal cell balancing structure in the internal embankment will allow water to enter Cell 2. When higher flows are present in the regional system and there is capacity in the reservoir, the main pump station will pump water into the reservoir. Discharges from the reservoir will typically occur when flows are needed to maintain a desirable salinity range in the estuary. Each cell of the reservoir is designed to discharge independently through separate structures into the perimeter canal as shown in **Figure 72**. Cell 1 will discharge via the S-471 structure while Cell 2 will discharge via the S-473 structure.

The project was authorized by the United States Congress in Section 7002(5) of the Water Resources Reform and Development Act of 2014 (Public Law 113-121). The District and USACE signed a project partnership agreement for this project on June 2, 2016. The District is funding the construction of the project and these costs will be applied to the District's 50% cost-share for CERP. The total project costs, including planning, design, land acquisition, and construction, is $832,106,000. The annual operational and maintenance costs are estimated at $3.9 million.

The District began construction on the C-43 Reservoir in November 2015; it is expected to be completed by November 2022. After construction is completed, the C-43 Reservoir project will undergo the operational testing and monitoring period, which is expected to last 1 to 2 years.

Water Reservation Rule for the Caloosahatchee River (C-43) West Basin Storage Reservoir

Whereas MFLs are established to define thresholds for significant harm to water resources, water reservations protect water for fish and wildlife or public health and safety by reserving it from consumptive use allocation. Specifically, Section 373.223(4), F.S. authorizes the District to "…reserve from use by permit applicants, water in such locations and quantities, and for such seasons of the year, as in its judgement may be required for the protection of fish and wildlife or the public health and safety". Any volume of water above what is required for the protection of fish and wildlife is available for allocation to consumptive uses.

The reservation of water is one of the mechanisms used to meet the federal and state requirements of protecting the water made available by projects constructed through CERP. Section 373.470, F.S. requires that before executing a project partnership agreement between the District and USACE and seeking federal funding, a reservation or allocation of water be completed. Protection of water needed for all CERP projects is a legal requirement to ensure that the water needed for the natural system will be available once the project is constructed and that the project benefits will be realized.

In 2014, the District established a water reservation rule for the C-43 Reservoir in anticipation of future construction to ensure that the surface water within the reservoir was reserved or protected from future allocation. This reservation ensures that all the surface water contained within and released, via operations, from the C-43 Reservoir is reserved from future consumptive use allocations (water use withdrawals). In essence, all of the water within the reservoir is protected for the natural system and will be available for the fish and wildlife located in the CRE, downstream of the S-79 structure.

EVALUATION OF EXISTING RECOVERY STRATEGY

As outlined above, the recovery strategy consists of two major elements: (1) the operation of the C-43 Reservoir and (2) a water reservation to protect the water within the C-43 Reservoir from future consumptive uses. The C-43 Reservoir Model was used to evaluate the existing recovery strategy to determine if the C-43 Reservoir will achieve recovery of the recommended MFL criteria outlined in **Chapter 6**.

Evaluation of the recovery strategy (C-43 Reservoir) was done by evaluating the future conditions (2040) by comparing the number of months that the flows were less than the minimum flow of 400 cfs at S-79 with and without the C-43 Reservoir project in place. This evaluation uses the AFSIR/WATBAL and SFWMM models in conjunction with the C-43 Reservoir Model (see **Figure 37** in **Chapter 7**). The other assumptions used in the future simulations are identical to those described in **Chapter 7**. Under future conditions, the model results show a total of 106 flow exceedances would occur without C-43 Reservoir in place while only 11 flow exceedances occur in the with project (C-43 Reservoir) scenario (**Figure 73**).

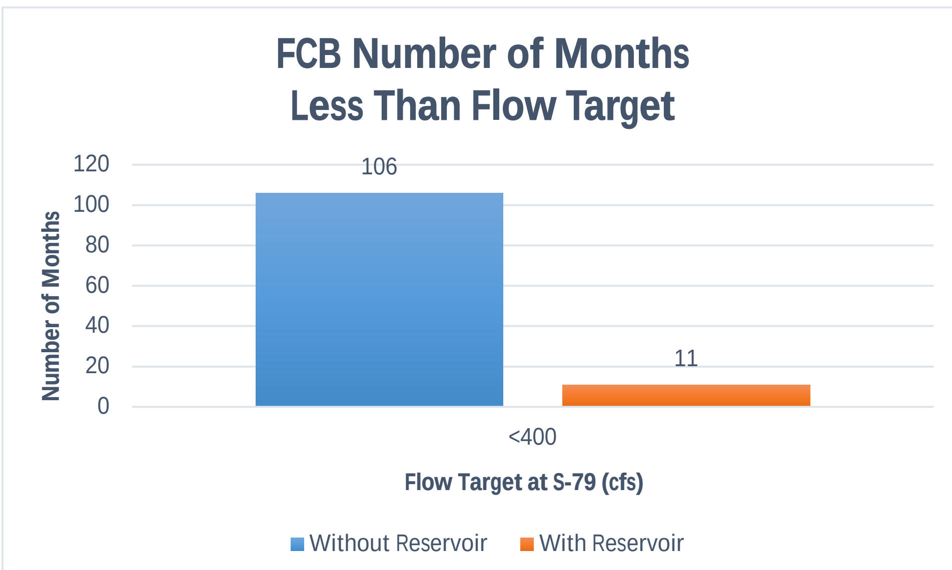


Figure 73. Number of months where flow exceedances are less than 400 cfs using the with and without C-43 Reservoir project scenarios.

The performance of the C-43 Reservoir was also evaluated by looking at the percentage of months the flow target was met during the 41-year POR using these same two future simulations (with and without project). Under the future condition, the without project scenario showed the minimum flow of 400 cfs was only met 78.5% of the time. Under the with project scenario (C-43 Reservoir) the minimum flow target of 400 cfs was met 97.8% of the time (**Figure 74**).

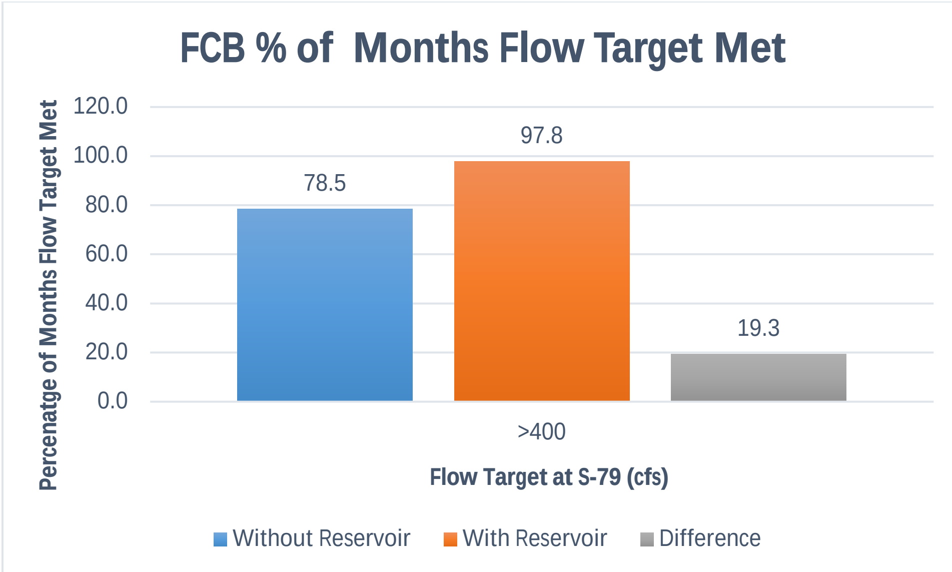


Figure 74. Percentage of time the minimum flow of 400 cfs is met with and without the C-43 Reservoir.

An additional modeling evaluation was also conducted to evaluate the performance of the recovery strategy by examining the frequency and duration of combined exceedances for flow and high salinity events and then comparing the with and without project scenarios. This evaluation couples both criteria together by evaluating when these combined events occur during the 39-year POR. The flow exceedances (< 400 cfs) are measured at S-79 using the SFWMM with the C-43 Reservoir Model while the combined flow and high salinity events are measured at Ft. Myers station using the CH3D model. A high salinity event was defined as salinity greater than 10 for 55 or more consecutive days. This future condition scenario provides important insights regarding the frequency and duration of high salinity events within the middle estuary without and with the recovery strategy in place. The modeling scenario called Future Condition Base Without Reservoir (FCBO) showed a total of 26 combined flow exceedance and high salinity events over the 39-year POR (**Figure 75**). The duration of these combined events varied from 31 to 212 days.

To evaluate the existing CRE MFL recovery strategy, a future model scenario, called FCW400, was performed using the same modeling assumptions described above (with 2040 demands and other future CERP components) but with the CRE recovery strategy in place. Under this with project model scenario, the C-43 Reservoir model attempts to meet the recommended minimum flow criteria using a daily time step and maximizes the performance of the C-43 Reservoir by tracking inflow, releases, and storage. Water is stored in the reservoir only when excess surface water flows are available in the system that would be discharged to tide. This future scenario does not use any supplemental flows from Lake Okeechobee to meet the minimum flow of 400 cfs at the S-79 structure. The FCBW400 simulation uses the same event criteria described above for both flow and salinity. Under the future condition, with the C-43 Reservoir in place, the model results show a total of 6 exceedances of combined flow and high salinity events over the 39-year POR in the model (**Figure 76**). When comparing the without and with project scenarios (**Figures 75** and **76**), not only were the frequency of these events significantly reduced (26 to 6 combined exceedance events) but the duration of these events was also greatly reduced from 212 to 120 days.

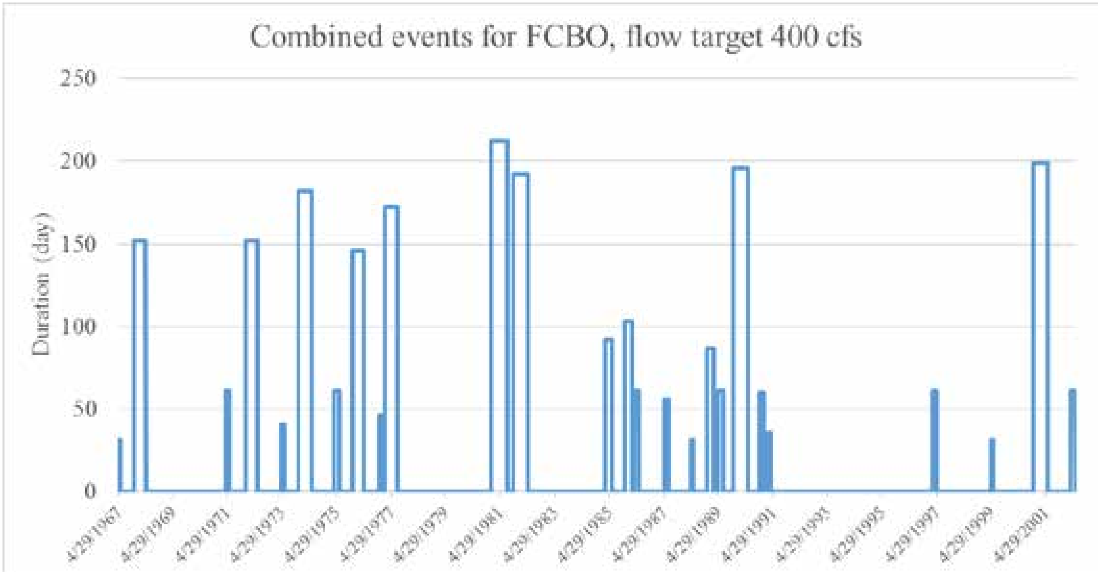


Figure 75. Combined flow exceedances and high salinity event for FCBO without the C-43 Reservoir and a flow target flow of 400 cfs.
(Note: The location of each bar indicates the timing of the events, the number of the bars indicates the number of events, and the height of the bar indicates the duration of each event.)

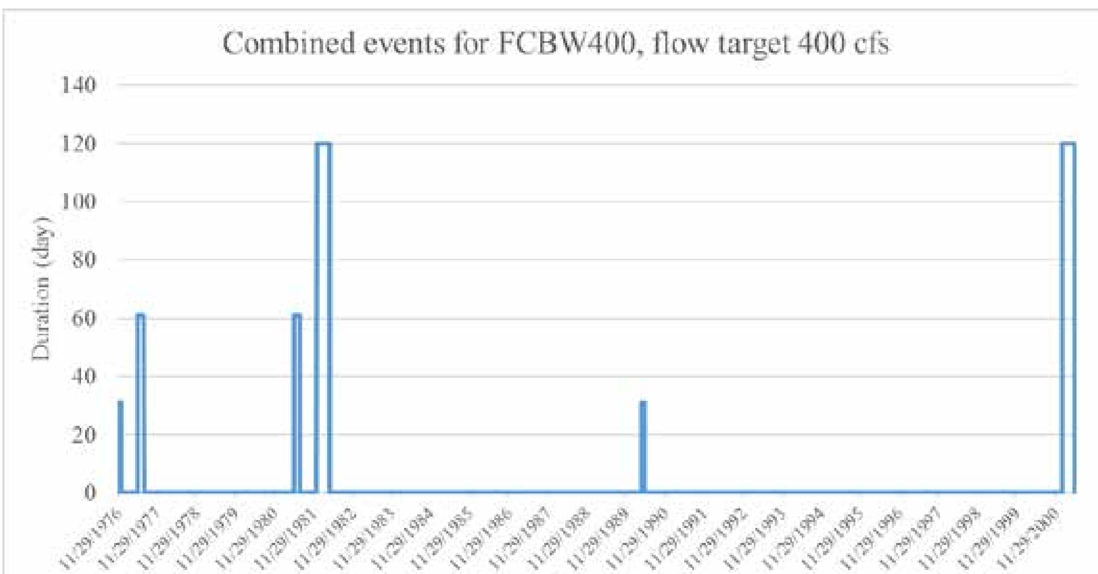


Figure 76. Combined flow exceedances and high salinity events for FCB400 with the C-43 Reservoir and a flow target flow of 400 cfs.
(Note: The location of each bar indicates the timing of the event, the number of the bars indicates the number of events, and the height of the bar indicates the duration of each event.)

Based on a review of the rainfall data for the CRE MFL watershed, most of these exceedance events are associated with significant to severe drought conditions. The MFL statutes and rules do not provide the authority or the legal basis to address drought events and the MFL criteria are not intended to drought-proof the system. The MFL rule does provide guidance (1) as to the magnitude and duration of events that may occur without causing significant harm and (2) provides a means to ensure that significantly harmful minimum flow events do not occur as a result of consumptive use withdrawals. The frequency and duration of these combined events are expected to be reduced further as operational, regulatory, and adaptive management strategies (e.g., operational changes for the C-43 Reservoir, water shortage criteria, etc.) are implemented to ensure protection of the water resources in the CRE.

As described in **Chapter 7**, the C-43 Reservoir is predicted to have a positive increase on the shoot biomass of *Vallisneria* within the CRE at Site 1. The reservoir in the FCB300 and FCB400 scenarios led to increased V_{shoot}, although there was no quantifiable seasonal differences in average values. Compared to the FCB scenario, V_{shoot} increased by 18.6 to 19.5% in the dry season and 27.4 to 28.5% in the wet season because the FCB300 and FCB400 inflow scenarios included the reservoir (**Figure 77**). The letters A and B above the graph show that there was a significant difference between the with and without reservoir scenarios. For more information about the Tape Grass Model, please see **Chapter 7**.

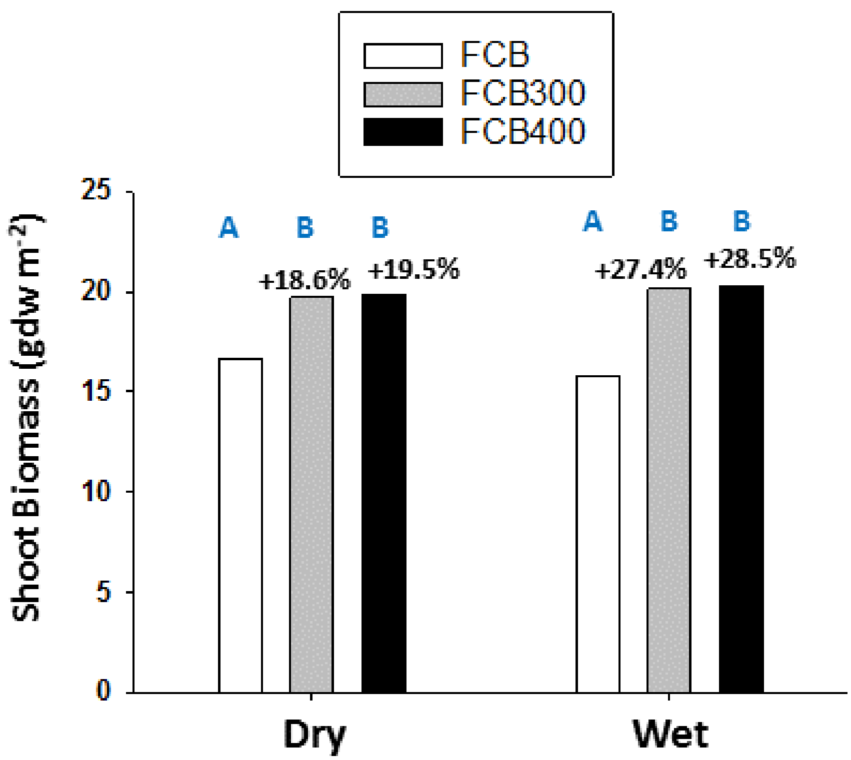


Figure 77. Results of 2-way ANOVA to assess the effects of season (dry versus wet) and inflow scenario (FCB, FCB300, or FCB400) on the average simulated tape grass shoot biomass at SAV Monitoring Site 1 in the upper CRE from January 1, 1967, through December 31, 2005. (Note: The letters A and B indicate statistical similarity among inflow scenarios within each season.)

In summary, based on staff's evaluation outlined above, the existing recovery strategy will provide recovery of the MFL with the recommended MFL criteria. Construction of the C-43 Reservoir is currently underway and is expected to be completed in 2022. This approved recovery strategy is being implemented expeditiously as required by Rule 62-40.473(7). The supplemental surface water flows provided by the C-43 Reservoir will provide the freshwater inflows needed to recover the MFL waterbody and maintain stable salinity regimes within the CRE during the dry season, once construction is completed and it becomes operational. These additional flows provided by the C-43 Reservoir during the dry season will provide the minimum flows necessary to prevent significant harm and protect the water resources in the CRE.

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APPENDIX A: ASSESSMENT OF THE RESPONSES OF THE CALOOSAHATCHEE RIVER ESTUARY TO LOW FRESHWATER INFLOW IN THE DRY SEASON

SCIENCE SUMMARY

Purpose of Study

The purpose of this study was to provide a comprehensive and quantitative assessment of the effects of freshwater inflow on the hydrology and ecology of the Caloosahatchee River Estuary (CRE) in the dry season (November–April). The dry season was chosen for this study because these are the times when freshwater inflows are diminished and negative responses from various ecological indicators are most likely to occur. It also coincides with the times when the minimum flows and minimum water levels (MFL) criteria are most likely to be exceeded. The objectives were (1) to compile and document information about freshwater inflows into and salinity distributions within the CRE, and (2) to examine the responses of a suite of ecological indicators to dry season freshwater inflows. This effort was conducted in support of the 2017 update to the MFL (Sections 373.042 and 373.0421, Florida Statutes [F.S.]) for the Caloosahatchee River (Rule 40E-8.221(2), Florida Administrative Code [F.A.C.]). Specifically, this study explored new data collected since adoption of the MFL, analyzed older data using updated statistical approaches, and applied recently developed ecological models.

Freshwater discharge, tides, and wind drive the estuarine salinity gradients, which influence all ecological processes in the water column and sediments. Organisms ranging in size and complexity from plankton to fish respond to fluctuations in inflow and salinity over a range of time scales. This study relied on multiple research components to examine inflow-salinity response patterns for phytoplankton, zooplankton, benthic communities, submersed aquatic vegetation (SAV), oyster beds, blue crabs (*Callinectes sapidus*), and sawfish (*Pristis pectinata*).

The Franklin Lock and Dam (S-79) located near Olga, Florida, serves as the upstream boundary for the CRE (**Figure A-1**). Freshwater inflow has been measured at this location since its completion in 1966. Although a majority of the total freshwater inflow is through the S-79 structure, there is ungauged input of fresh water from tributaries and groundwater in the Tidal Basin downstream of the structure. Recent estimates of the Tidal Basin's contribution have improved with data availability and advancements in modeling. However, all analyses of indicator responses were conducted relative to measured inflow at the S-79 water control structure. The contribution of the Tidal Basin was incorporated into the final assessment of the magnitude of total inflows to the estuary (total inflows = S-79 + Tidal Basin).

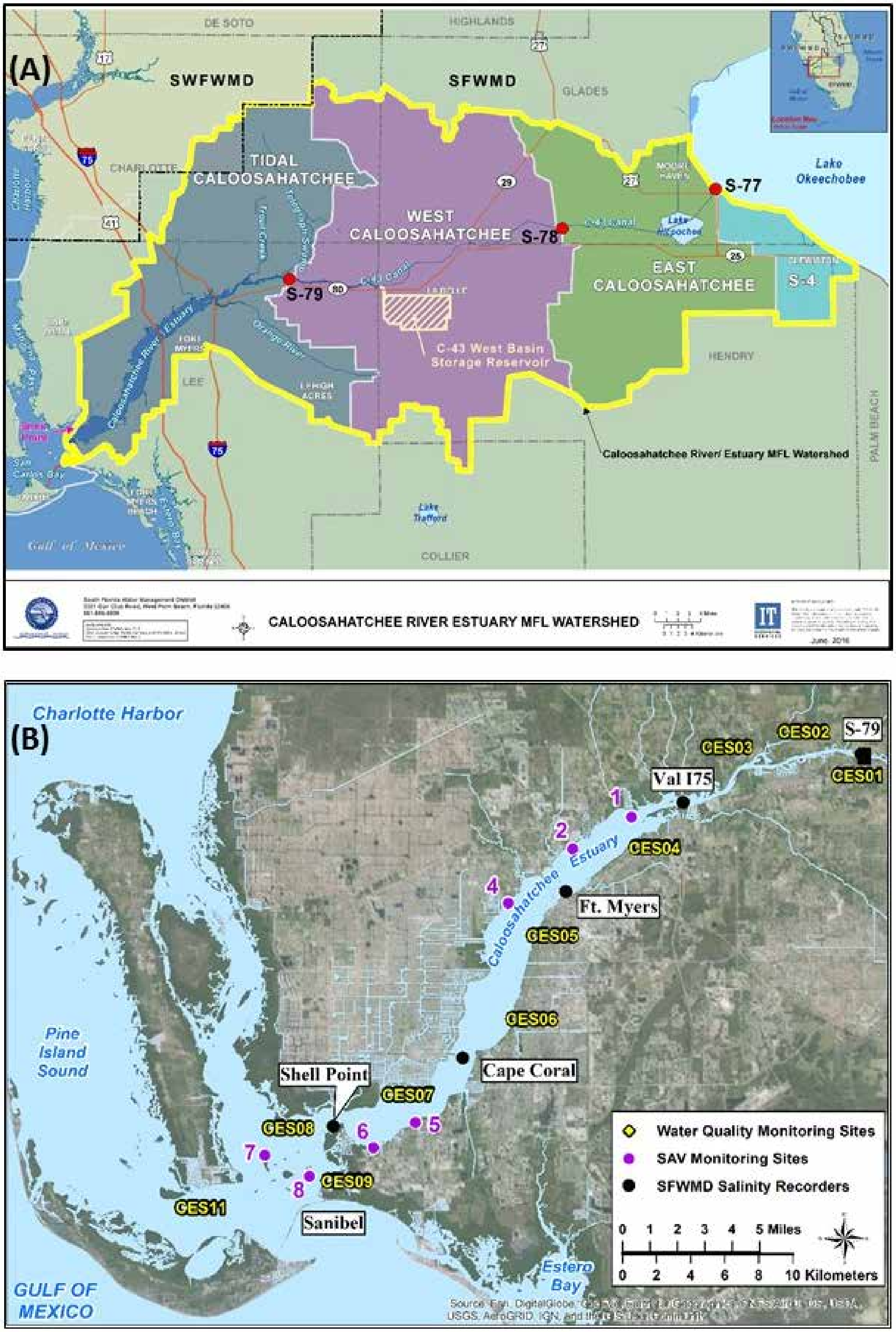


Figure A-1. (A) The CRE MFL Watershed with its subwatersheds and major water control structures, and (B) locations for the monitoring of water quality, SAV, and salinity recorders for the CRE.

Background Information

Alterations of the South Florida Landscape and CRE MFL Watershed

The CRE and the C-43 Canal were connected to Lake Okeechobee through the evolution of the Central and Southern Florida Flood Control Project (C&SF Project). The C&SF Project is a complete system of canals, storage areas, and water control structures spanning the area from Lake Okeechobee to both the east and west coasts, and from Orlando south to the Everglades. It was designed and constructed during the 1950s and 1960s by the United States Army Corps of Engineers (USACE) to provide flood control and improve navigation and recreation. Most of the waterbodies within the C&SF Project have specific regulation schedules that are federally mandated by USACE.

The South Florida Water Management District (SFWMD or District) is the local sponsor of the C&SF Project. In its capacity as local sponsor, SFWMD operates and maintains the C&SF Project. The operations require water to be moved out of certain waterbodies when stages are above the regulation schedule to provide flood protection.

As a result of the C&SF Project, the modern South Florida aquatic landscape is highly engineered featuring ~3,380 kilometers (km) of canals, ~1,225 water control structures, more than 70 pumping stations, heavily managed wetlands, densely populated coastal watersheds, and highly impacted estuaries (Ogden et al. 2005, Obeysekera et al. 2011). This includes the region between Lake Okeechobee and the Gulf of Mexico encompassing the CRE MFL Watershed and CRE (**Figure A-1A**; Buzzelli et al. 2015a). The portion of the watershed located upstream of the S-79 structure is referred to as the C-43 Watershed or C-43 Basin. The portion of the watershed located downstream of the S-79 structure is referred to as the Tidal Caloosahatchee Subwatershed or Tidal Basin. Flows from the S-79 structure to the CRE are part of the C&SF Project. Water management must balance resource needs by protecting the natural system while simultaneously providing water supply, flood control, and recreation opportunities. As a result of these structural alterations, the availability of water that can be delivered to the CRE from the regional system to meet these needs is constrained.

In addition to the alterations described above, a multitude of other structural and physical alterations have occurred to the CRE MFL Watershed, historic Caloosahatchee River (now the C-43 Canal), and CRE. These alterations changed the historical hydrologic conditions of the CRE MFL Watershed and downstream waterbodies. A network of secondary and tertiary canals in the CRE MFL Watershed is connected to the C-43 Canal and CRE. These canals provide navigational access or convey water for both drainage and irrigation to accommodate agricultural, urban, and other land uses in the watershed. Based on the 2012 land use land cover data, the primary land use type within the CRE MFL Watershed today is agricultural, which comprises 41.5%. Urban and built up land use comprises 18%, and wetlands comprise approximately 15.1%.

Historically, the Caloosahatchee River was sinuous as it originated near Lake Flirt ~2 miles (3.2 km) east of La Belle at Fort Thompson. Beginning in the 1880s, the river channel was straightened, deepened, and connected to Lake Okeechobee. This resulted in a loss of 76 river bends and 8.2 miles (13.2 km) of river length (Antonini et al. 2002). Dredging alterations continued and, by 1918, three combination lock and spillway structures had been constructed at Moore Haven, Citrus Center, and Fort Thompson (USACE 1957, Section 6.B.6). Flows within the historic Caloosahatchee River (now the C-43 Canal) are controlled through the operation of multiple water control structures (S-77, S-78, and S-79) as these structures regulate downstream freshwater transport. The final lock and dam structure (S-79) was completed in 1966 at Olga to assure freshwater supply and prevent upstream saltwater intrusion. Discharges from Lake Okeechobee and the C-43 Canal (between the S-77 and S-79 structures) are regulated by USACE.

Early descriptions of the CRE characterize it as barely navigable due to extensive shoals and oyster bars (Sackett 1888). Some of the alterations that have occurred include dredging a large navigational channel (Intracoastal Waterway) and secondary navigational channels, removing oyster bars upstream of Shell Point for roadway construction, removing the gulf bar at the mouth of the CRE, and the creation of two islands for construction of the Sanibel Causeway across the mouth of San Carlos Bay. Seven automobile bridges and one railroad bridge now connect the north and south shores of the estuary.

There are other more recent significant changes that affect water availability including the Lake Okeechobee Regulation Schedule that went into effect in 2008 (LORS2008), adaptive protocols for Lake Okeechobee, and establishment of a restricted allocation area for the Lake Okeechobee Service Area (LOSA). The restricted allocation area rule for LOSA that was adopted in 2008 limits allocations from Lake Okeechobee and integrated conveyance canal systems that are hydraulically connected to and receive surface water from Lake Okeechobee (Balci and Bertolotti 2012). This includes the C-43 and C-44 canals. The current regulation schedule (LORS2008) regulates the stage in Lake Okeechobee approximately one foot lower than the previous Water Supply and Environment Regulation Schedule. The adaptive protocols for Lake Okeechobee are intended to provide operational flexibility to facilitate environmental benefits without impacting other lake uses. The adaptive protocols were modified for use with the LORS2008 in the *Final Adaptive Protocols for Lake Okeechobee Operations* (SFWMD 2010), which was finalized on September 16, 2010.

The potential for removing the existing structural and physical alterations affecting the C-43 Canal and the CRE may not be economically or technically feasible. Much of the existing development within the downstream waterbodies is dependent upon the modern functions of these alterations (e.g. flood protection, navigation, water supply, and transportation). For this reason, SFWMD has been strategically focused on making improvements within the watershed rather than the downstream estuary. Programs and projects to improve water regimes and ecosystem health, or both, include the Dispersed Water Management Program; Caloosahatchee Storage/Treatment Project; Comprehensive Everglades Restoration Plan (CERP), including the Caloosahatchee River (C-43) West Basin Storage Reservoir (C-43 Reservoir); Northern Everglades and Estuaries Protection Program (NEEPP); and other smaller projects (SFWMD 2017).

Freshwater Inflow and Estuaries

Small estuaries and embayments with subtropical climates and managed inflow are particularly susceptible to reduced freshwater input on scales of days (event-scale) to years (Schlacher et al. 2008, Buzzelli 2011, Azevedo et al. 2014). Inflows are managed because many estuarine rivers have dams at the upstream boundary (Montagna et al. 2002a) similar to the CRE. Low inflow increases hydrodynamic residence time as the upstream encroachment of saltier water can establish a cascade of low inflow-related ecological responses (Sheldon and Alber 2006, Wan et al. 2013).

Submarine light often increases throughout the estuary with the reduced input of colored dissolved organic matter that freshwater inflow provides (Bowers and Brett 2008, Chen et al. 2015). Reduced flushing coupled with enhanced light in the surface layer can stimulate the rapid proliferation of phytoplankton in the upper estuary on scales of days to weeks (Murrell et al. 2007, Lancelot and Muylaert 2011, Cloern et al. 2014). Zooplankton and ichthyoplankton assemblages often shift upstream with their food resources (phytoplankton) while remaining within favorable salinity zones (Flannery et al. 2002). However, there is the possibility of habitat impingement and/or compression if upstream movement of planktonic assemblages is bounded by a water control structure (Crowder 1986, Tolley et al. 2010). The overall biological productivity in estuaries is proportional to freshwater inflow (Livingston et al. 1997, Gillson 2011).

Saltwater encroachment can alter the composition and density of the macrobenthic community upon which many estuarine fish and crustaceans are dependent (Palmer et al. 2011, Montagna et al. 2013). The freshwater macrophyte *Vallisneria americana* (tape grass) provides essential habitat in the oligohaline portion of many estuaries. However, it is very sensitive to increases in the frequency and duration of elevated salinity (Doering et al. 2002, French and Moore 2003, Rozas and Minello 2006). Increased salinity also can impact the survival of the eastern oyster (*Crassostrea virginica*) through the introduction of marine parasites and predators (Livingston et al. 2000, Petes et al. 2012). The life histories of many coastal fish populations rely on favorable salinity gradients as they utilize estuaries as nursery and feeding areas (Whitfield et al. 2012, Stevens et al. 2013, Sheaves et al. 2015). Finally, long-term reductions in freshwater inflow can be associated with declining harvests of important fishery species (Wilber 1994, Gillson 2011).

Fluctuations in freshwater inflows over time scales ranging from weeks to years have altered salinity regimes and impacted the ecology of the CRE (Chamberlain and Doering 1998a, Barnes 2005). Changes in freshwater inflows and salinity have been shown to affect the distribution and dynamics of many taxa and communities including phytoplankton and zooplankton (Tolley et al. 2010, Radabaugh and Peebles 2012), SAV (Doering et al. 2001, 2002, Lauer et al. 2011), oysters and pathogens (La Peyre et al. 2003, Barnes et al. 2007, Volety et al. 2009), fauna inhabiting oyster reefs (Tolley et al. 2005, 2006), and fishes (Collins et al. 2008, Heupel and Simpfendorfer 2008, Simpfendorfer et al. 2011, Poulakis et al. 2013, Stevens et al. 2013).

Freshwater Inflow and the CRE

South Florida has a subtropical climate featuring dry (November–April) and wet (May–October) seasons (Childers et al. 2006, Moses et al. 2013, Buzzelli et al. 2015a). Event-scale weather, extreme intraannual seasonal variations in precipitation, and longer-term climatic fluctuations (3 to 6 years) are incorporated into water management (Obeysekera et al. 2007). In order to include both a wet and a dry season, a water year is defined as the time from May 1 to April 30 of the subsequent year. A water year is named for the year in which it ends.

The long-term annual average (Water Year 1997 [WY1997]–WY2014) rainfall within the CRE MFL Watershed was 51.5 inches with 21.9% in the dry season and 78.1% in the wet season (**Figure A-2A**). Freshwater discharge at the S-79 structure represents the combined contribution of rainfall-driven runoff from the CRE MFL Watershed as well as releases from Lake Okeechobee. The average annual total inflow (WY1997–WY2014) was 1.8 x 10^6 acre-feet (ac-ft) (2,220 x 10^6 cubic meters [m^3]). Over this time period, the relative contributions from Lake Okeechobee, the C-43 Watershed upstream of S-79, and the Tidal Basin downstream of S-79 averaged 31.6%, 47.6%, and 20.8%, respectively (**Figure A-2B**).

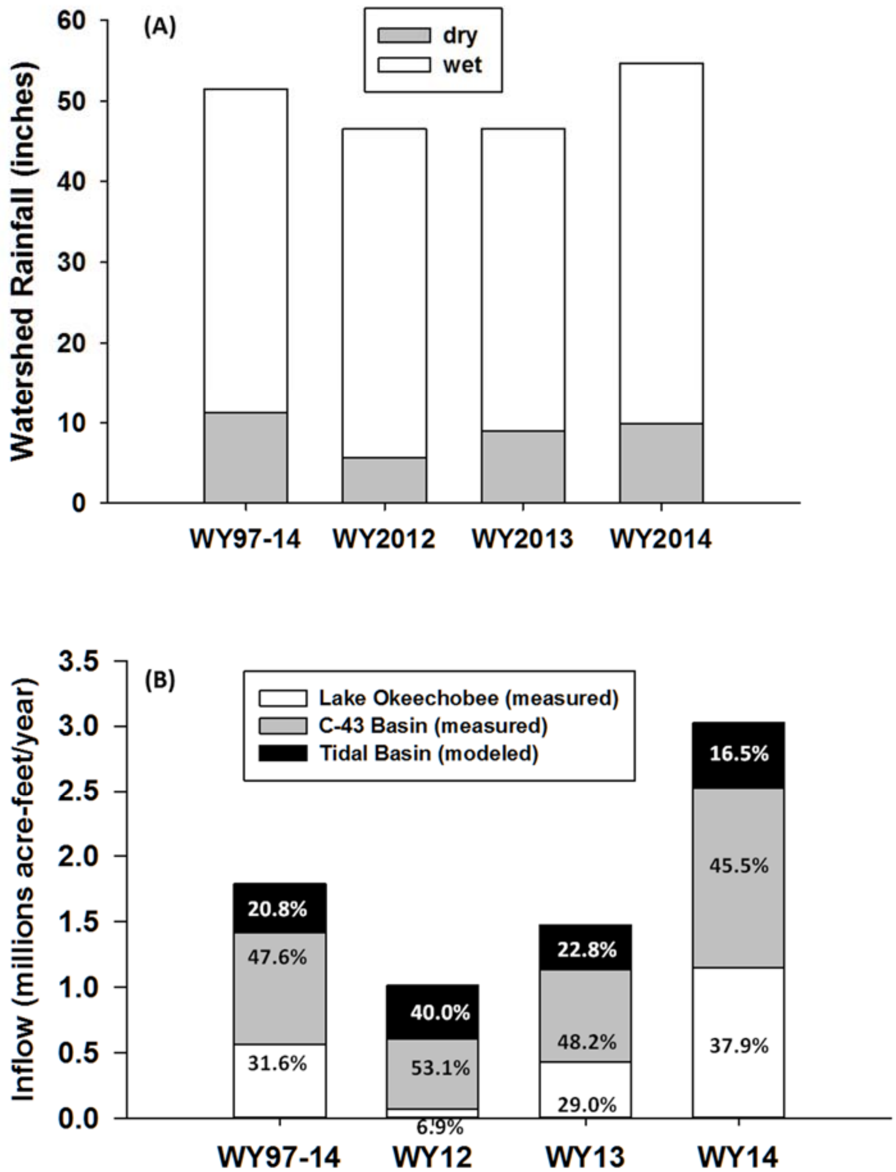


Figure A-2. (A) Total rainfall to the CRE MFL Watershed by water year and season and (B) stacked bar chart for the total freshwater inflow. (Note: Included are the long-term averages from WY1997–WY2014, WY2012, WY2013, and WY2014.)

The CRE is bounded upstream by the S-79 structure and downstream by San Carlos Bay at the mouth (**Figure A-1A**). The surface area of the CRE is 67.6 square kilometers (km^2; 6,764 hectares; 16,715 acres) with an average depth of 2.7 meters (Buzzelli et al. 2013a). Average flushing time ranges from 5 to 60 days (Wan et al. 2013, Buzzelli et al. 2013d). A variety of physical, chemical and biological variables are regularly monitored by SFWMD and other organizations (**Figure A-1B**). Freshwater inflow has been measured at S-79 since 1966 and is reported as daily average cubic feet per second (cfs). Surface and bottom salinity have been monitored at multiple locations (S-79, Val I75, Ft. Myers, Cape Coral, Shell Point, and Sanibel) since the 1990s and is reported as average daily values. Salinity is derived from a dimensionless ratio and therefore has no units in reporting (Millero 2010). The distribution and density of SAV have been determined at the upper stations (1, 2, and 4) since 1998 and the in the lower estuary (5, 6, 7, and 8) bi-monthly since 2004. Oyster population attributes have been monitored seasonally at multiple locations in the lower estuary near Shell Point since 2000.

The term “ecohydrology” was coined to describe the integrative management of coastal basins based on the linkages among inflows, circulation, environmental conditions, habitat attributes, and biological integrity (Peterson 2003, Wolanski et al. 2004). Essential to this conceptualization are resource-based approaches to quantify minimum freshwater inflows (Chamberlain and Doering 1998b, Alber 2002). This approach seeks to identify the historical inflow regime, the biological resources to be protected, and the environmental conditions required to sustain them and determine inflow regimes needed to maintain the desired conditions (Palmer et al. 2011). Choosing an indicator resource that responds to freshwater inflow in a timeframe appropriate for management can be problematic (Dale and Beyeler 2001, Alber 2002). In many cases, there are limited data for, or changes in, the indicator resource that preclude extraction of useful information from the existing data.

The Caloosahatchee River MFL criteria were based on the salinity tolerance of *Vallisneria americana* (Doering et al. 1999, 2001, 2002, SFWMD 2003). *Vallisneria* was selected as an indicator because of its location in the estuary, its sensitivity to enhanced salinity, and its important habitat functions (sediment stabilization, nursery area, and food web support for invertebrate and vertebrate fauna). An independent peer review in 2000 of the SFWMD MFL document (SFWMD 2000) emphasized four problematic research areas: (1) lack of a hydrodynamic/salinity model; (2) lack of a numerical population model for *Vallisneria americana*; (3) no quantification of the habitat value of *Vallisneria* beds; and (4) lack of documentation of the effects of MFL flows on downstream estuarine biota (SFWMD 2003). A research program was initiated in 2001 to address some of these concerns and a review of the MFL criteria was conducted (SFWMD 2003).

There has been much effort towards addressing the problematic areas identified in the peer review. Salinity data collected at 15-minute intervals at multiple locations between S-79 and Shell Point have been central to the development and calibration of a three-dimensional hydrodynamic model (Qiu 2002, 2006, Qiu and Wan 2013, Wan et al. 2013). Additionally, the long-term time series of salinity at the Ft. Myers station (1992–present) and other locations are essential to a wide range of water quality and ecological studies supporting water management (Balci and Bertolotti 2012, Buzzelli et al. 2015a). The Florida Department of Environmental Protection (FDEP), SFWMD, and United States Geological Survey jointly conducted a flow monitoring program from October 2008 to March 2013 to measure stage and flow at several locations in the Tidal Basin of the CRE (Telegraph Creek, Orange River, Popash Creek, Billy’s Creek, Hancock Creek, Marker 52, and Shell Point). Lee County has monitored Whiskey Creek since April 1994. These data were collected to support further development and calibration of the Tidal Basin Model (Wan and Konyha 2015).

The distribution and abundance of *Vallisneria* have been documented since 1997 (Buzzelli et al. 2015a). Additionally, studies of the responses of *Vallisneria* to variable salinity and temperature (Doering et al. 2001, 2002, Bartleson et al. 2014) provided an information base for both empirical assessments and the development of a simulation model (this document). Site-specific assessment of *Vallisneria* habitat value has been impeded by the greatly reduced distribution and density of *Vallisneria* since droughts in 2001 and 2007–2008. Oyster beds were identified as stationary indicators of salinity and freshwater inflow in the lower estuary (Volety et al. 2009, Buzzelli et al.

2013b). Oyster population attributes have been monitored in the lower CRE as part of CERP since 2005 (RECOVER 2014).

The Conservancy of Southwest Florida filed a petition on September 3, 2010, requesting immediate initiation of rulemaking to revise the Caloosahatchee River MFL Rule. The SFWMD Governing Board denied this petition. However, SFWMD committed to review and update the Caloosahatchee River MFL Rule after conducting the appropriate scientific analyses based on the best available information.

Methods

Description of Component Studies

This effort was composed of 11 component studies to evaluate the effects of reduced freshwater inflow on the CRE in the dry season (**Table A-1**). While the estimation of estuarine inflow requirements using multiple indicators offers a system of checks and balances, the quantitative assessment of the responses of a particular resource to variable levels of inflow can be very difficult (Adams et al. 2002).

Table A-1. List of component studies and the basic description of research methods. (Note: Studies 2 through 11 resulted in estimates of indicator inflow magnitudes.)

	Study	Method
1	Hydrodynamics	Influence of alterations on hydrodynamics
2	Inflow versus Salinity	Monthly freshwater-salinity relationships at Ft. Myers
3	Water Quality	Fine-scale relationships between water quality and inflow
4	Zooplankton	Inflow, zooplankton impingement, and habitat compression
5	Ichthyoplankton	Relationships between ichthyoplankton and inflow
6	Benthic Fauna	Macrofauna-salinity patterns relative to inflow
7	*Vallisneria* Data	Empirical relationships between *Vallisneria*, salinity, and inflow
8	*Vallisneria* Model	Model exploration of *Vallisneria*, salinity, light, and inflow
9	Oyster Habitat	Assess conditions for oyster survival in the lower CRE
10	Blue Crabs	Relationships between blue crab landings, rainfall, and inflow
11	Sawfish	Area and volume of sawfish habitat with variable dry season inflow

Implications of Uncertainty

Uncertainty is a fundamental property that can propagate through computational schemes and contribute to interpretative errors (Regan et al. 2002, Lehrter and Cebrian 2010). It is important that the uncertainty associated with proposed environmental actions be evaluated, quantified, and properly explained so that all stakeholders can better connect changes in ecological systems to effective scientific inquiry and improved management (Lamon et al. 1996, Halpern et al. 2006).

Limits in data quantity, data quality, and an understanding of dynamic processes increase uncertainty in predictive models (Reckhow 1994). Although assessments of environmental risk using models can be inherently uncertain, the information contained in uncertainty can be applied to benefit environmental decision making (Reckhow 1994). For example, data gaps and missing information can be identified by evaluating uncertainty and variability (Ahn and James 2001).

Unlike environmental management of rivers or lakes, salinity serves as the connection between biotic resources in the receiving basin and the rate of freshwater inflow in estuaries (Alber 2002). Spatial and temporal salinity variations are complicated by wind and atmospheric frontal passages, tidal exchange, and vertical mixing. Thus, it is very difficult to directly relate freshwater inflows, hydrodynamic processes, and biological responses in coastal basins. Difficulties arise from a combination of scalar mismatches, complexity and uncertainty, temporal and spatial lags, and an overall lack of data.

This study included estimations of freshwater inflow associated with observed or simulated responses of selected estuarine indicators. These estimations were based on data, information, assumptions, discussions, and calculations, which carry varying amounts of inherent and systematic uncertainty. Despite inevitable uncertainty, this document provides the best available information through which to better understand the potential responses of selected indicators to salinity regimes within the CRE in the dry season.

Quantification of Indicator Freshwater Inflows in the Dry Season

This study applied elements of a resource-based approach to the quantification of freshwater inflows that might be limiting to the ecological functioning of the CRE in the dry season. The component studies emphasized the relationships between the indicators and inflows through the S-79 structure. The term "indicator inflow" or Q_I was defined as the S-79 inflow threshold below which there might be detrimental effects. There were 11 different approaches to estimate Q_I (Study Component Studies 2 through 11).

1. Component Study 1 utilized hydrodynamic modeling as a tool to explore changes in circulation and salinity caused by structural alterations at the estuary scale but did not provide estimates of inflows relative to estuarine response variables.
2. Component Study 2 used the relationship between average monthly inflow at S-79 and average monthly salinity at the Ft. Myers station to estimate the quantity of fresh water associated with a salinity value of 10 from WY1993 to WY2013.
3. Component Study 3 emphasized the relationship between low inflow and elevated chlorophyll *a* concentrations (CHL) to estimate Q_I when CHL in the upper CRE was greater than the impaired estuarine waters target of 11 micrograms per liter (µg L^{-1}) (FDEP 2009). This approach was applied independently to both empirical and model-derived CHL values.
4. Component Study 4 estimated Q_I as the inflow threshold below which the upstream movement of the zooplankton community would be impinged against the S-79 structure.
5. Component Study 5 utilized salinity tolerances of ichthyoplankton to estimate the habitat area with reduced inflow.

6. Component Study 6 estimated Q_I from inflows on the days when the salinity in the upper CRE was greater than the tolerance range associated with the characteristic benthic macrofauna community.
7. Component Study 7 extracted dry season days where the salinity at the Ft. Myers station ranged from 9 to 10 from WY1993 to WY1999 when *Vallisneria* was abundant to calculate Q_I.
8. Component Study 8 applied a *Vallisneria* simulation model to identify the salinity and inflows where *Vallisneria* experienced net mortality.
9. Component Study 9 extracted days where the salinity at Cape Coral was 20 to 25 from WY2005 to WY2014 concurrent with oyster monitoring to calculate Q_I.
10. Component Study 10 examined the relationships between rainfall and Lee County blue crab catch data.
11. Component Study 11 assessed the impact of inflows on the area of favorable habitat for the endangered sawfish in the dry season.

Results

Summaries of Component Studies

Component Study 1: Three-dimensional Model Evaluation of Physical and Structural Alterations of the Caloosahatchee River and Estuary: Impact on Salt Transport

Hydrodynamic modeling of estuaries provides a platform to assess the effects of physical alterations on hydrodynamics, transport, and mixing. This study component utilized a three-dimensional hydrodynamic model (Curvilinear Hydrodynamic Three Dimensional Model or CH3D) of the CRE to compare simulated salinities between the existing condition and the reversal of five historical physical alterations to the estuary. The alterations evaluated were the (1) removal of the S-79 water control structure; (2) removal of the downstream causeway (Sanibel); (3) backfill of the oyster bar near the estuary mouth; (4) backfill of the navigation channel; and (5) reestablishment of predevelopment bathymetry. Model results indicated that refilling the navigation channel had profound effects with a 20% reduction in dry season salinity. The reduced salt transport was more pronounced with the predevelopment bathymetry because the estuary was much shallower. Increased estuary depth and cross-sectional area significantly increase salt transport to the upper estuary. Increased salt transport can push biologically relevant isohalines further upstream depending upon freshwater inflow conditions.

Component Study 2: Analysis of the Relationship between Freshwater Inflow at S-79 and Salinity in the CRE 1993–2013

The upstream migration of salt with reduced freshwater inflow alters the composition and productivity of oligohaline habitats in estuaries. This process can be problematic in subtropical estuaries with regulated freshwater inflow such as the CRE in southwestern Florida. This study component examined relationships between average monthly inflow (Q) and mid-estuary salinity (S) from 1993 to 2013. An exponential decay equation was fit to the inflow-salinity (Q-S) relationship for each water year (May 1 to April 30). Annual equations were used to estimate the inflow rate associated with salinity equaling 10 at the Ft. Myers monitoring station (Q_{calc}). Inflows varied both intra- and interannually. Q_{calc} ranged from 70 to 773 cfs with an average of 445 ± 218 cfs. At the estuary and annual scales, the quantity of fresh water to support a particular salinity target varied greatly. This variance was related to the variations in freshwater inputs from both the C-43 Watershed located upstream of the S-79 structure and the downstream Tidal Basin.

Component Study 3: Relationships between Freshwater Inflows and Water Quality Attributes during the Dry Season in the CRE

Decreased flushing with reduced inflow can lead to the deposition of phytoplankton biomass and bottom water hypoxia in estuaries. This study component utilized event-scale water quality data, long-term monitoring of CHL, and simulation modeling of phytoplankton dynamics to evaluate low freshwater inflows that could contribute to water quality problems in the upper CRE. The highest CHL and lowest dissolved oxygen (DO) concentrations occur in the upper CRE under low inflows. Although more research is needed, it is hypothesized that dry season inflows of less than approximately 500 to 600 cfs may promote bottom water hypoxia in the deeper channel of the upper CRE. Field and model results indicated that CHL concentrations greater than the water quality standard of 11 $\mu g\ L^{-1}$ were associated with inflows of 469 ± 689 cfs and 269 ± 493 cfs, respectively. Low level inflows (< 500 cfs) need to be further studied to better quantify the discharge required to mitigate the potential for hypoxia in the upper CRE.

Component Study 4: Zooplankton Response to Freshwater Inflow in the CRE

Freshwater inflow to some estuaries, including the CRE, is regulated through control structures. Zooplankton assemblages provide an essential food web link whose position in the estuary fluctuates with inflow. Unfortunately, zooplankton habitat can be both impinged and compressed due to the presence of a water control structure as inflow is reduced in the dry season. This study assessed impingement and habitat compression for zooplankton under reduced inflow. Data used were from a CRE study conducted by Florida Gulf Coast University from 2008 to 2010. Zooplankton samples were collected monthly at each sampling site at night during a flood tide. The centers of abundance (COA) for the 13 taxa investigated migrated downstream and upstream as freshwater inflow increased and decreased, respectively. Both habitat compression and impingement were potentially harmful for zooplankton assemblages in the estuary. Impingement was possible if inflow from the S-79 structure ranged from 98 to 566 cfs and averaged 412 ± 165 cfs. Almost all taxa investigated (except *Menidia*) experienced habitat compression if the COA was < 12 km downstream of S-79.

Component Study 5: Ichthyoplankton Response to Freshwater Inflow in the CRE

Ichthyoplankton communities are key components of food webs in the upper, oligohaline reaches of most estuaries. This study analyzed historical (1986–1989) data to evaluate effects of salinity and freshwater inflow on ichthyoplankton communities in the CRE. Abundance of ichthyoplankton was greatest when the 30-day inflows at S-79 averaged between 151 and 600 cfs. Juvenile fish appeared to prefer salinities < 10 and their abundance was centered just downstream of Station 2 near Beautiful Island. Flows at S-79 associated with a salinity of 10 near Beautiful Island averaged 237.5 ± 255.5 cfs. Flows less than this could result in loss of favorable habitat.

Component Study 6: Summary and Interpretation of Macrobenthic Community Properties Relative to Salinity and Inflow in the CRE

The composition, distribution, and density of benthic invertebrate communities (macrofauna) can be used as indicators of salinity and inflow for estuaries. The goal of this study component was to explore the relationships between inflow, salinity, and benthic macrofauna in the CRE. Benthic samples were collected every 2 to 4 months at seven stations during two periods (February 1986–April 1989 and October 1994–December 1995). The abundance, diversity, and composition of the macrofaunal community were determined relative to observed fluctuations in salinity. Four distinct zones emerged based on salinity ranges and the composition of the macrobenthic community. Conditions conducive to maintain the characteristic community observed during the sampling periods in the most upstream zone (salinity = 0 to 4, 0 to 7 km from S-79) occurred on 54% of dry season days from 1993 to 2012. The indicator inflows (Q_I) ranged from 0 to 3,720 cfs and averaged 501 ± 525 cfs for the days where salinity was 3 to 4 (sample size [n] = 181).

Component Study 7: Relationships between Salinity and the Survival of *Vallisneria americana* in the CRE

Vallisneria americana is sensitive to increased salinity in many estuaries, including the CRE. Much of the *Vallisneria* observed from 1993 to 1999 in the CRE has been lost since droughts in 2001 and 2007–2008. This study examined relationships between *Vallisneria* and salinity through change-point analysis, assessment of long-term patterns of abundance, and exploration of the effects of salinity exposure time. Change-point analysis revealed salinity thresholds of 4, 9, and 15. Dry season average daily salinity was ~5 and rarely exceeded 10 when *Vallisneria* was abundant from 1993 to 1999. Indicator inflows (Q_I) ranging from 0 to 3,160 cfs and averaging 545 ± 774 cfs, were associated with dry season salinity values of 9 to 10 (n = 63) at the Ft. Myers station from 1993 to 1999. In contrast, *Vallisneria* was virtually absent from 2007 to 2013 as dry season average daily salinity exceeded 10. Negative changes in shoot density can be rapid as ~50 to 60% of the aboveground material was lost if salinity was > 10 for two to three weeks. These results highlight the effects of both the magnitude and duration of environmental conditions that can inhibit *Vallisneria* survival in the CRE.

Component Study 8: Development and Application of a Simulation Model for *Vallisneria americana* in the CRE

Monitoring of *Vallisneria americana* densities in the upper CRE from 1998 to 2007 was accompanied by mesocosm experiments to determine relationships between salinity and growth. This study built upon these efforts by developing a simulation model to examine the effects of temperature, salinity, and light on *Vallisneria* survival and biomass in the upper CRE from 1998 to 2014. The effects of salinity on *Vallisneria* mortality were explored using an eight-year experimental model based on favorable conditions from 1998 to 1999. Using the experimental model, the dry season salinity was systematically increased in 5% increments until the net annual biomass accumulation of *Vallisneria* was negative. A five-fold increase in grazing was required to stabilize model biomass under optimal conditions. A 55% salinity increase to 12 promoted shoot mortality in the experimental model. Annual inflow-salinity relationships for the Ft. Myers station were used to estimate that dry season inflows ranging from 15.2 to 629.0 cfs and averaging 342 ± 180 cfs were associated with a salinity of 12 at the Ft. Myers station. Model results suggested that an estimated 85.4 and 86.7% of the shoots were lost in the dry seasons of 2001 and 2007, respectively.

Component Study 9: Assessment of Dry Season Salinity and Freshwater Inflow Relevant for Oyster Habitat in the CRE

Short- and long-term alteration of salinity distributions in estuaries with variable freshwater inflow affects the survival, abundance, and extent of oyster habitat. The objective of this study was to evaluate salinity conditions at two locations, Cape Coral and Shell Point, in the CRE. Salinity data from the 2006 through 2014 dry seasons (November–April) were categorized relative to oyster habitat criteria and related to freshwater inflow. Daily salinity was within the appropriate range for oysters (10–25) on 70.1% of the observations. Daily inflow ranged from 0 to 2,000 cfs and averaged 296 ± 410 cfs when salinity ranged from 20 to 25 at Cape Coral in the dry season. The influence of the marine parasite *Perkinsus marinus* (Dermo) is limited due to the subtropical climate where temperature is low when salinity is high (dry season) and temperature is high when salinity is low (wet season). Overall salinity patterns were favorable for oyster survival at the upstream extent of oyster habitat in the CRE.

Component Study 10: Ecohydrological Controls on Blue Crab Landings and Minimum Freshwater Inflow to the CRE

A long-term record (28 years) was used for blue crab landings in the CRE to establish relationships between (1) changes in hydrology and changes in water resource function and (2) the magnitude of the functional loss and time to recover. Annual catch per unit effort (CPUE), computed from monthly landings of crabs and measures of fishing effort, represented the resource function. Annual landings expressed as both unadjusted and de-trended CPUE were found to be significantly correlated with hydrologic variables, rainfall, and freshwater inflow during the previous year's dry season. Increases in CPUE from one year to the next were also positively related to dry season rainfall in the first of the two years. Geometric mean functional regressions and Monte Carlo simulations were used to identify the dry season rainfall associated with losses of water resource function (CPUE) that required 1, 2, or 3 years of average dry season rainfall to recover. A spectral analysis indicated that time series of both dry season rainfall and blue crab catch had periodicities of 5.6 years. A Monte Carlo analysis revealed that the rainfall associated with two- and three-year recoveries had return intervals of 5.8 and 8.2 years, respectively.

Component Study 11: Relationships between Freshwater Inflow, Salinity, and Potential Habitat for Sawfish (*Pristis pectinata*) in the CRE

The smalltooth sawfish is an endangered species that historically ranged from Texas to North Carolina. The distribution and abundance of sawfish have declined due to over fishing and habitat loss. Presently, the CRE is an important sawfish nursery. Juvenile sawfish habitat can be characterized as nearshore environments < 1 meter in depth, where salinities range from 12 to 27. This study quantified sawfish habitat with variable inflow to the CRE in the dry season using a combination of bathymetric analyses and hydrodynamic modeling. Inflows of 150 to 300 cfs positioned the 12 and 27 salinities in the shallowest part of the estuary (10 to 30 km downstream). Specifically, the area of sawfish habitat was greatest (5.7 km^2) when inflow through the S-79 structure was 270 cfs in the dry season. Under reduced inflow, the habitat migrated into the channel above Beautiful Island where it was compressed against S-79. Higher inflows pushed the position of salinity of 27 (S_{27}) out of the estuary.

Quantification of Indicator Freshwater Inflows in the Dry Season

While there were 10 separate component studies that generated values for Q_I, the water quality component provided both empirically-based and modeled estimates using the same selection criteria (**Table A-2** and **Figure A-3**). Among 11 different calculations, the estimated magnitude of Q_I was least from the phytoplankton model (269 ± 493 cfs), the sawfish habitat assessment (270 cfs), analysis of ichthyoplankton data (237 ± 255 cfs), and evaluation of conditions relative to oyster tolerances (296 ± 410 cfs). While an inflow rate of 545 ± 774 cfs was estimated to inhibit

Vallisneria survival, the modeling exercise predicted that inflow rates less than 342 ± 180 cfs could lead to *Vallisneria* mortality.

Table A-2. Summary of component studies, the method used to estimate the indicator inflow (Q_I), and the range and average + standard deviation (Avg + SD) values for Q_I (cfs). (Note: The median value for Q_I over all estimates is provided [362 cfs].)

Component Study		Method	Q_I (cfs)	
			Range	**Avg + SD**
1	Hydrodynamics	Hydrodynamic model used to evaluate long-term structural modifications to the CRE	Not applicable (NA)	NA
2	Inflow versus Salinity	Based on calculated inflow at S-79 associated with S-10 at the Ft. Myers station from monthly average long-term data (WY1993–WY2013; n = 16)	70–720	445 ± 218
3	Water Quality - Data	Estimated using monthly average dry season CHL > 11 µg L^{-1} observed at CES03 linked to daily freshwater inflow (n = 8).	0–2,270	469 ± 689
	Water Quality – Model	Estimated using daily average dry season CHL > 11 µg L^{-1} predicted in the upper CRE linked to daily freshwater inflow (n = 58).	0–2,450	269 ± 493
4	Zooplankton	Estimated using monthly zooplankton center of abundance (2008–2010) and lagged inflows with conditional regression (n = 7).	98–566	412 ± 165
5	Ichthyoplankton	Estimated using monthly icthyoplankton center of abundance (2008–2010) and 30-day average salinity at the Ft. Myers station (n = 11).	62–1191	237 ± 255
6	Benthic Fauna	Benthic fauna data used to establish optimal salinity in the upper reaches of the CRE (optimum salinity = 3–4). Long-term (WY1993–WY2012) inflow at S-79 and salinity at BR31 were used to calculate inflow on dry seasons days meeting optimal salinity criteria (n = 181).	0–3,720	501 ± 525
7	*Vallisneria* Data	Estimated using maximum salinity tolerance (salinity = 9–10) and dry season Ft. Myers station salinity data from the period when *Vallisneria* was abundant (WY1993–WY1999; n = 63).	0–3,160	545 ± 774
8	*Vallisneria* Model	Simulation series where dry season daily salinity was proportionally increased until *Vallisneria* biomass stabilized in optimized 8 year-model version. Estimated inflows from dry season days in 1998–1999 where salinity at Val Site 1 ranged from 6.3 to 6.5 (n = 32).	0–526	342 ± 180
9	Oyster Habitat	Estimated from maximum salinity tolerance (salinity = 20–25) and dry season daily salinity at Cape Coral from WY2005 to WY2014 (n = 422).	0–2,000	296 ± 410
10	Blue Crabs	Estimated using rainfall/discharge associated with significant harm to Lee County blue crab fishery from WY1981 to WY2013 (n = 2).		400 ± 57 [a]
11	Sawfish	Estimated using hydrodynamic model to quantify relationship between the area that was < 1 meter and favorable salinity range (12–27 or 18–30) and inflow.		270 [b]

a. Average from two estimates.

b. Only one value estimated for sawfish using the 12–27 salinity range.

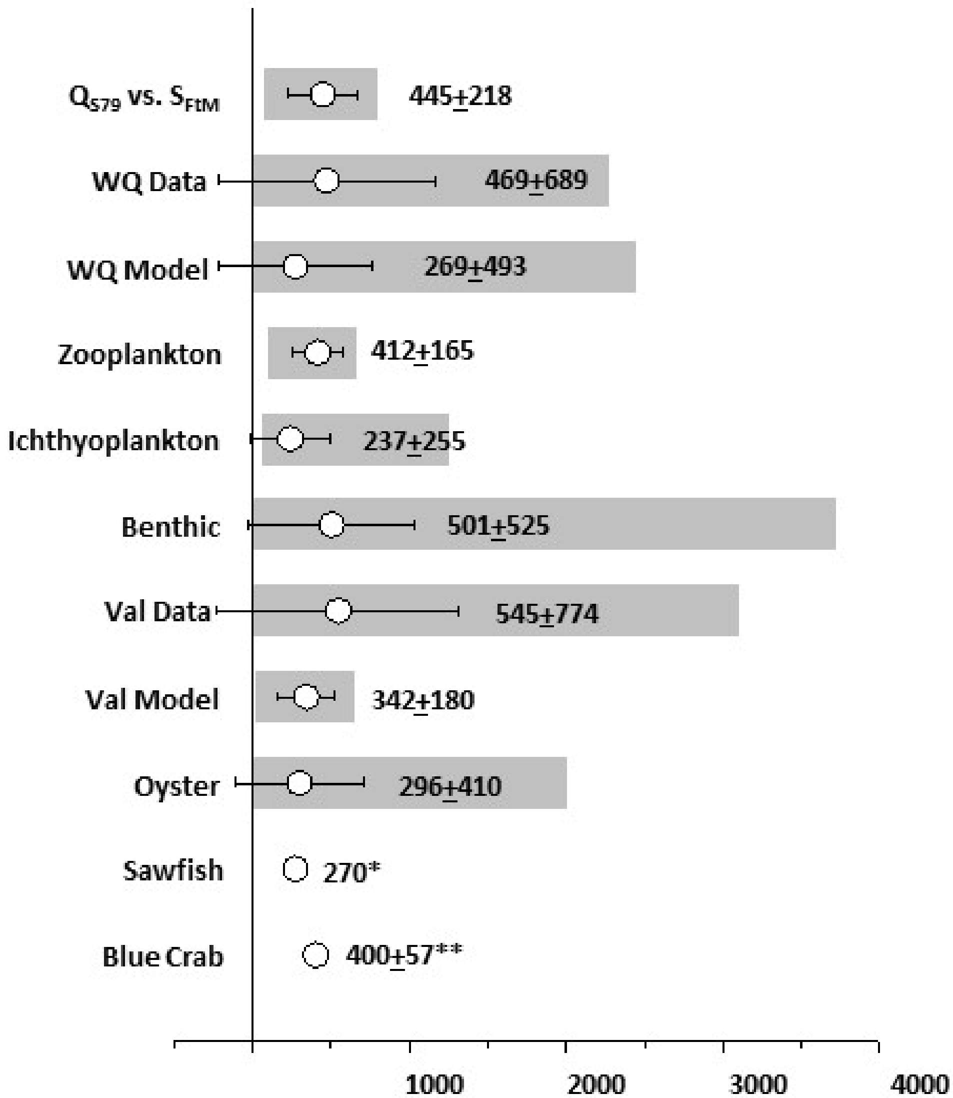


Figure A-3. Graphical results showing the range (bar) and average + standard deviation (point + error bar and text) of the estimated indicator inflows (Q_I) for each of the component studies. (Notes: See **Table A-2** and text for calculation details related to each estimate. *Only one value was estimated for sawfish using the 12–27 salinity range. **Average from two estimates.)

There was a wide range of sample sizes used to estimate Q_I among the calculations (2 to 422). For example, 16 annual values were used in Component Study 2 (S-79 inflow versus salinity at the Ft. Myers station) compared to 181 daily values derived in Component Study 6 (benthic fauna). Four of the approaches used the salinity requirements of an indicator resource as a guide to select corresponding dry season inflows (benthic fauna, *Vallisneria* data, oysters, and sawfish). Each of these four estimates generally resulted in a wide range of possible inflows and therefore, large standard deviations that were greater than the average values. On the other hand, estimates among the customized approaches from the other five component studies (S-79 inflow versus salinity, zooplankton, icthyoplankton, *Vallisneria* model, and blue crabs) had narrower ranges and less variance (**Table A-2**). For example, Q_I estimated for zooplankton and ichthyoplankton assemblages averaged 412 ± 165 cfs and 237 ± 255 cfs, respectively. As a result of the method, a single value for Q_I was estimated from assessment of sawfish habitat (270 cfs). A different optimum salinity range from 18 to 30 was evaluated for juvenile sawfish in the CRE after receiving public comment. Habitat area was recalculated based on the same hydrodynamic modeling results and bathymetric data. The result of this analysis showed that, as discharge increases, habitat area and volume decreased (see Addendum to Component Study 11).

Discussion

The purpose of this study was to provide a comprehensive and quantitative assessment of the effects of freshwater inflow during the dry season on the hydrology and ecology of the CRE in the dry season (November–April). It is unique in its scope to incorporate multiple indicators along the length of the estuary that respond to fluctuations in discharge or salinity on time scales ranging from days (water quality) to decades (blue crab catch data).

There were three important findings from this study:

1. The magnitude of minimum indicator inflows (Q_I) from the S-79 structure ranged from 237 cfs to 545 cfs among the 11 estimates.
2. Seasonally averaged S-79 inflows less than the Q_I for each indicator could result in phytoplankton blooms in the upper CRE (< 10 km from S-79), compress the water column habitat for zooplankton and icthyoplankton against the structure, alter the composition of the macrobenthic community in the upper estuary, prevent the survival of *Vallisneria*, shrink the available habitat for the endangered sawfish, and lead to reduced harvest of blue crabs the following year.
3. Flow through S-79 accounts for 82% of the total inflow. The Tidal Basin inflows account for the remaining 18%. Assuming a median Q_I at S-79 of 400 cfs, the Tidal Basin flows are estimated at 88 cfs for a total inflow of 488 cfs.

Increased salinity through combinations of seawater encroachment and reduced freshwater input influences species composition, physiological processes, and trophic dynamics (Gonzalez-Ortegon and Drake 2012). For example, long-term reductions in discharge to Apalachicola Bay in the northern Gulf of Mexico altered the food web leading to decreased biological productivity over time (Livingston et al. 1997). Therefore, it is important to describe the freshwater dry season inflows necessary to establish estuarine salinity gradients in both dynamic (water column) and static (benthic) habitats (Wolanski et al. 2004, Palmer et al. 2011).

Salinity varies over many time scales through complex hydrodynamic processes that integrate rainfall, surface inflows, submarine groundwater discharge, wind events, and tidal exchanges (Zheng and Weisberg 2004). Thus, simple correlations between inflow and salinity may be influenced by ungauged freshwater inputs. The diffuse inputs through submarine groundwater discharge is particularly difficult to quantify and model (Langevin 2003, Burnett et al. 2006). Recent efforts to measure and model the contribution of the Tidal Basin to total freshwater inflow to the CRE provided an estimate of ~18% over all dry seasons from 1966 to 2014 (Wan and Konyha 2015; this study). The relative contribution of the Tidal Basin ranged from 5 to 90% with values < 10% in very wet dry seasons (1995, 2005, and 2006) to values > 70% in the driest times (1982, 1990, 2001, and 2008). This potentially important source of fresh water must be incorporated into hydrodynamic models to account for changes in salinity that affect estuarine processes.

The balance between downstream transport of fresh water and the upstream encroachment of salinity creates gradients that influence all biogeochemical processes and patterns. The gradient can be represented by lines of equal salinity (e.g. isohalines) whose positions fluctuate up and down the estuary with freshwater inflow(s), tidal cycles, and meteorological phenomena (e.g. fronts, winds, and storms). Particular isohalines provide useful indications of desirable (or undesirable) salinity conditions for sentinel organisms or communities (Jassby et al. 1995). For example, low salinity conditions indicative of a functional oligohaline benthic community served as the most upstream biological indicator. Salinity at this upstream location is extremely sensitive to fine scale changes in freshwater inflow. This sensitivity combined with the complexity and dynamism of macrobenthic assemblages accounted for the variability of the estimated Q_I (501 ± 525 cfs)—a range associated with salinity zones for characteristic macrobenthic communities in the dry season (Palmer et al. 2015).

Estimated mean daily dry season inflows of 300 to 550 cfs were associated with suitable dynamic and stationary habitats (water column and *Vallisneria*, respectively) located in the upper estuary around Beautiful Island (~10–15 km from S-79). Dry season inflows within this range should serve to maintain the area of maximum phytoplankton production and biomass from 9 to 16 km downstream. Maintaining the area of maximum CHL $\geq$ 12 km downstream should diminish the potential for the accumulation of phyto-detritus and hypoxia in the upstream bottom water. Overall, the relationships between dry season inflow (< 500 cfs), the magnitude and position of the CHL maximum concentrations, and bottom water hypoxia in the upper CRE are complex and poorly understood.

Vallisneria was historically observed from 1993 to 1999 from Beautiful Island to the Ft. Myers station (Hoffaker 1994, Bortone and Turpin 2000). The acute sensitivity of this organism to increased salinity makes it an excellent candidate for the resource-based approach of prescribing freshwater inflows (Chamberlain and Doering 1998a, 1998b, Doering et al. 2002). Dry season freshwater inflows of 545 ± 774 cfs from 1993 to 1999 promoted the maximum tolerable salinity (9 to 10) for the survival of *Vallisneria*. Conversely, the *Vallisneria* habitat disappeared as the average salinity at the Ft. Myers station exceeded 10 from 2007 to 2013. *Vallisneria* habitat in the CRE has not recovered from drought-induced stress in 2001 and 2007–2008 when salinity was > 10 for 4 to 5 months. Loss of mature shoots greatly inhibits the potential for habitat reestablishment. There were signs of recovery on a scale of 3 to 6 years as salinity declined from 2003 to 2006. However, increased salinity in the upper CRE from 2007 to 2009 and again in 2012 severely limited the potential for *Vallisneria* survival.

There were three different indicator inflow estimates from analyses centered near the Ft. Myers station (~20 km downstream of S-79). Ft. Myers represents a location in the middle of the CRE just downstream of the *Vallisneria* beds where variations in basinwide total freshwater inflow are the main drivers for salinity (Wan et al. 2013, Buzzelli et al. 2015a). This study estimated that S-79 inflows averaging 445 ± 218 cfs were related to a salinity of 10 at this location. While a coarse-scale assessment, there are wide variations in the inflow from S-79 that accounts for a target salinity at Ft. Myers (e.g. 10). For example, more inflow is required from S-79 to maintain the magnitude and position of indicator isohalines when Tidal Basin inputs are diminished due to extended periods of drought.

Inflows from S-79 ranging from ~225 to 425 cfs maintain zooplankton and ichthyoplankton assemblages in downstream locations (~10–20 km and 10–30 km, respectively). Peak zooplankton abundance is often located downstream of the maximum CHL but can migrate far upstream under severely reduced inflow. It is under these circumstances the water column biota could experience habitat impingement and compression against S-79. As with water quality, there should be further study of the effects of low inflow on planktonic dynamics in the upper estuary.

Oyster habitat located from Cape Coral to the mouth of the CRE served as the most seaward indicator of freshwater inflows. While oysters are excellent indicators to detect changes in and responses to environmental conditions, salinity in the lower estuary is highly influenced by oceanic processes. Assessment of the time series of inflows based on oyster salinity criteria (salinity of 20–25) resulted in reasonable but variable estimates of Q_I (296 ± 409 cfs). The relatively high variability was because a wide salinity range was applied (20–25) at a downstream location (Cape Coral, ~30 km from S-79).

Estimates of the indicator inflows for the two mobile fauna species (blue crabs and sawfish) resulted from widely different approaches. Salinity gradients must be adequate for these two populations to most effectively utilize the estuary as a nursery (Wilbur 1994, Poulakis et al. 2013). The blue crab CPUE being proportional to freshwater inputs in the previous dry season demonstrates both the connectivity and lags between rainfall, inflows, salinity, and biotic responses. At the seasonal time scale, dry season mean monthly inflows of ~270 cfs would position the 12 to 27 salinity range ~10 to 30 km downstream of S-79, thus maximizing the potential sawfish habitat area. Dry season mean monthly inflows < 270 cfs could confine the sawfish habitat to the deeper, upper CRE where there is much less shoal area and lead to habitat compression against the structure. Upstream migration into a bathymetrically compressed habitat potentially places juvenile sawfish in closer proximity to larger predators such as bull sharks (*Carcharhinus leucas*) (Poulakis et al.2011).

COMPONENT STUDIES

Component Study 1: Three-Dimensional Model Evaluation of Physical and Structural Alterations of the Caloosahatchee River and Estuary: Impact on Salt Transport

Detong Sun and Yongshan Wan

Abstract

Hydrodynamic modeling of estuaries provides a platform to assess the effects of physical alterations on hydrodynamics, transport, and mixing. This study component utilized a three-dimensional hydrodynamic model (Curvilinear Hydrodynamic Three Dimensional Model or CH3D) of the CRE to compare simulated salinities between the existing condition and the reversal of five historical physical alterations to the estuary. The alterations evaluated were the (1) removal of the S-79 water control structure; (2) removal of the downstream causeway (Sanibel); (3) backfill of the oyster bar near the estuary mouth; (4) backfill of the navigation channel; and (5) the reestablishment of predevelopment bathymetry. Model results indicated that refilling the navigation channel had profound effects with a 20% reduction in dry season salinity. The reduced salt transport was more pronounced with the predevelopment bathymetry because the estuary was much shallower. Increased estuary depth and cross-sectional area significantly increase salt transport to the upper estuary. Increased salt transport can push biologically relevant isohalines further upstream depending upon freshwater inflow conditions.

Introduction

Hydrodynamic processes integrate freshwater inputs, wind events, and tidal exchanges to establish salinity conditions and modulate biodiversity and biological productivity. Estuaries are very sensitive to anthropogenic changes including urbanization, physical alterations of the estuarine systems, nutrient enrichment, and climate change (Alber 2002). Physical alterations, such as dredging and dams, change natural inflows, impact hydrodynamics and mixing with the coastal ocean, and dramatically affect salinity and water quality gradients in the estuary (Day et al. 1989). Anthropogenic changes to tributary rivers can have pronounced influence on both the quality and quantity of freshwater inputs to estuaries. Additionally, deep navigational channels can alter circulation, increase the upstream encroachment of saltwater, and promote hypoxia and anoxia.

The impacts of physical alterations on estuarine systems are noted worldwide. The Wadden Sea in the Netherlands and the Mississippi Delta in the United States serve as two examples of how physical alterations have changed coastal systems. In the Wadden Sea, coastal land reclamation was designed to protect natural resources while allowing for urban and agricultural development (Saundry and Cleveland 2011). In the Mississippi Delta, changes following the construction of dikes that cut the sources of riverine sediment, and dredging of canals led to significant hydrologic changes (Deegan et al. 1984, Barras et al. 2004, Day et al. 2005). In both cases, large areas of coastal ecosystem have been altered or destroyed.

Such changes are also evident in South Florida where river channels were dredged and widened for navigational purposes and water control structures were constructed near the heads of the estuaries (Kimes and Crocker 1999, Antonini et al. 2002, Ogden et al. 2005). The modern landscape is highly engineered featuring ~3,380 km of canals, ~1,225 water control structures, more than 70 pumping stations, heavily managed wetlands, densely populated coastal watersheds, and highly impacted estuaries (Ogden et al. 2005, Obeysekera et al. 2011). These structural alterations have dramatically changed the watershed hydrological conditions as well as the geomorphology of the rivers and estuaries. In addition, agricultural and municipal demands for fresh water have increased. All these modifications have altered freshwater discharges to the estuaries (Balci and Bertolotti 2012).

Physical alterations at the landscape scale may have possibly irreversible impacts on estuarine ecosystems (Dyer and Orth 1994). Quantitative evaluation of these alterations remains a difficult task. Previous estuarine studies used hydrodynamic models to investigate saltwater intrusion in dredged navigational channels. Liu et al. (2001) utilized a vertical (laterally integrated) two-dimensional numerical model to study the hydrodynamic characteristics and extended saltwater intrusion in the Tanshui River estuarine system (Taiwan). The UnTRIM San Francisco Bay-Delta model, an unstructured grid hydrodynamic model, was used to study saltwater intrusion associated with deepening the Sacramento Deep Water Ship Channel (MacWilliams et al. 2009). In Louisiana, a semi-implicit version of Estuary and Coastal Model was used to study saltwater intrusion in navigation channels in Lake Pontchartrain (Georgiou 1999). In Florida, the Environmental Fluid Dynamics Code hydrodynamic model of the St. John's River was used to study the impact from dredging Jacksonville Harbor (USACE 2008). A more recent study applied the Finite Volume Coastal Ocean Model to explore the effects of changes to the navigational channel on circulation in Tampa Bay (Zhu et al. 2015).

The CRE has a watershed characterized by extensive agriculture and urbanization, is influenced by both unregulated and regulated freshwater inflow, and contains valuable biological resources (Chamberlain and Doering 1998a, Doering et al. 2006, Balci and Bertolotti 2012). Through climatic variations, landscape modification, flood protection, and managed operations, the CRE can experience reduced freshwater inflow during the dry season. In many estuaries, reduced freshwater inflow over time can result in the landward encroachment of salinity (Cloern and Jassby 2012). In the case of the CRE, upstream saltwater intrusion can reduce the extent of vegetated freshwater habitat (i.e., *Vallisneria americana*), impact community composition in the water column and benthos, and compress the oligohaline area of the estuary that is essential to a variety of faunal populations (Doering et al. 2002, Simpfendorfer et al. 2011, Stevens et al. 2013).

The objective of this study was to use a hydrodynamic model to evaluate the effects of physical alterations on salinity distribution in the CRE. CH3D was applied to the CRE. This study intended to quantify and rank the effects of different physical and structural alterations over the past century on modern day estuarine salinity patterns.

Methods

Study Site

The Caloosahatchee River and Estuary are located in Southwest Florida (**Figure A-4**). The modern day C-43 Canal runs 67 km from Lake Okeechobee to the Franklin Lock and Dam (S-79 structure), which marks the upstream boundary of the estuary that extends 42 km downstream to Shell Point. The system has been modified to provide for navigation, water supply, salinity control, and flood protection on both a local and regional scale (Chamberlain and Doering 1998a, Doering et al. 2006). The CRE is a funnel-shaped estuary whose width ranges from ~0.2 km in the upper portion to ~2.5 km near the mouth. The total surface area of the estuary is about 65 km^2 (Buzzelli et al. 2013a). The narrow section between the S-79 structure and Beautiful Island (~15 km downstream) was physically altered by channelization with an average depth of ~6 meters (m) while the downstream estuary has an average depth of 1.5 m.

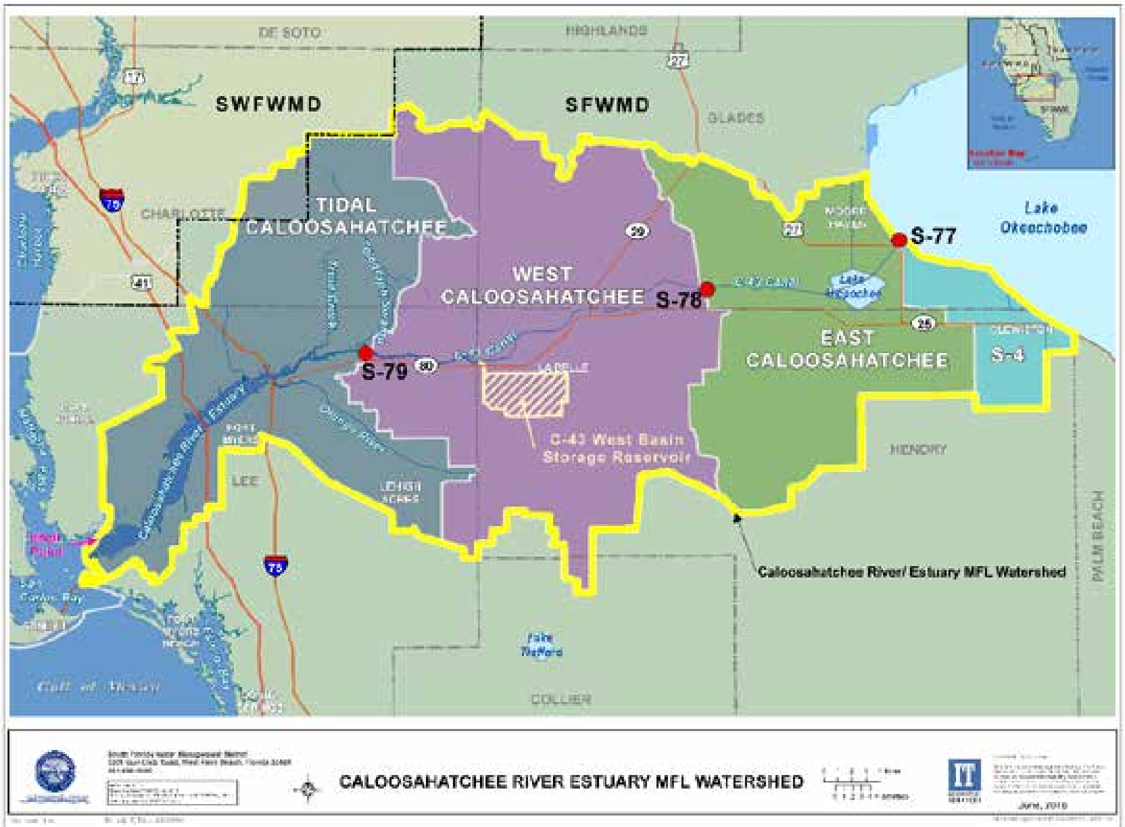


Figure A-4. The CRE MFL Watershed with its subwatersheds and major water control structures. (Note: The future location of the C-43 Reservoir is also shown.)

Alterations within the CRE MFL Watershed

The CRE and the C-43 canal were connected to Lake Okeechobee through the evolution of the C&SF Project. The C&SF Project is a complete system of canals, storage areas, and water control structures spanning the area from Lake Okeechobee to both the east and west coasts, and from Orlando south to the Everglades. It was designed and constructed during the 1950s by USACE to provide flood control and improve navigation and recreation. In its role as a local sponsor, SFWMD is subject to balancing the water resource needs by providing flood control, water supply, recreation, and protection for the natural system. As a result of structural alterations to the watershed, the existing C&SF Project has constraints on the availability of water that can be delivered to the CRE from the regional system.

In addition to the alterations described above, a multitude of other structural and physical alterations have occurred to the CRE MFL Watershed, historic Caloosahatchee River, and the CRE. These alterations changed the historical hydrologic conditions of the CRE MFL Watershed and its receiving waterbodies. The CRE MFL Watershed is a system that has been highly altered from its natural state by human intervention to meet multiple objectives. Various land uses in a watershed dictate water demands and runoff volumes to estuarine receiving waters located downstream of S-79. A network of secondary and tertiary canals exists in the CRE MFL Watershed that is hydrologically connected to the C-43 Canal and the CRE. These canals are used for navigational access or to convey water for both drainage and irrigation to accommodate existing agriculture, urban development, and other land uses in the watershed.

The primary land use type within the CRE MFL Watershed today is agricultural, which comprises 41.5% of the total area. Urban and built up land uses occupy the next largest group (18%), followed by wetlands (15.1%), and upland forest (14%).

Historically, the Caloosahatchee River, present day C-43 Canal, was a sinuous river, originating near Lake Flirt, ~2 miles (3.2 km) east of La Belle at Fort Thompson. Beginning in the 1880s, the river channel was straightened, deepened, and connected to Lake Okeechobee. This resulted in a loss of 76 river bends and 8.2 miles (13.2 km) of river length (Antonini et al. 2002). Dredging alterations continued and, by 1918, three combination lock and spillway structures had been constructed at Moore Haven, Citrus Center, and Fort Thompson (USACE 1957, Section 6.B.6). Flows within the historic Caloosahatchee River (now the C-43 Canal) are controlled through operation of multiple water control structures (S-77, S-78, and S-79), and these structures regulate freshwater inflows to the downstream estuary. The final lock and dam structure (S-79) was completed in 1966 at Olga to assure freshwater supply and prevent upstream saltwater intrusion. Discharges from Lake Okeechobee and the C-43 Watershed or Basin (between the S-77 and S-79 structures) are regulated by USACE for various purposes, including flood control, water supply, and navigation. The modern C-43 Canal spans 70 km from the S-77 structure at Lake Okeechobee to the S-79 structure (**Figure A-4**).

The total effect of these alterations has been the loss of surface water storage in the CRE MFL Watershed, which has altered the magnitude, timing, and distribution of freshwater inflows to the estuary at the S-79 structure. As is typical of a watershed characterized by extensive drainage features (Hopkinson and Vallino 1995), runoff is more variable with higher wet season discharges and lower dry season discharges. Large volumes of fresh water during the wet season can flush all salt water from the tidally influenced sections of the waterbody. By contrast, inflow at S-79 can stop entirely during the dry season. Salt water intrudes to S-79, sometimes reaching a salinity of 20 (Chamberlain and Doering 1998a, 1998b). Fluctuations of this magnitude at the head and mouth of the system cause mortality of organisms at both ends of the salinity gradient (Doering et al. 2002).

The first recorded survey of the waterbodies (CRE and historic Caloosahatchee River) within the watershed was conducted by Captain W.M. Black of the United States Army Engineers in 1887 (Black 1887). This survey indicated that the estuary was much shallower than today. An extensive shoal (< 1.6-m depth) spanned the mouth where the estuarine river discharged to San Carlos Bay. This shoal was part of an extensive tidal delta that bordered the eastern portion of the bay. Navigation was inhibited along the entire length by the shoal and oyster bars, which extended ~27 km upstream to Fort Myers. The historical river channel from Fort Myers to LaBelle was shallow (~1 m), long (~70 km), and crooked. Early descriptions of the estuary characterize it as barely navigable due to extensive shoals and oyster bars (Sackett 1888). Some of the alterations that have occurred include dredging a large navigational channel (Intracoastal Waterway) and secondary navigational channels, removing oyster bars upstream of Shell Point for roadway construction, removing the gulf bar at the mouth of the CRE, and the creation of two islands for construction of the Sanibel Causeway across the mouth of San Carlos Bay. Seven automobile bridges and one railroad bridge now connect the north and south shores of the estuary.

The potential for removing the existing structural and physical alterations affecting the historic Caloosahatchee River (C-43 Canal) and the CRE may not be feasible. Much of the existing development within these downstream waterbodies is dependent upon the conditions these alterations currently provide (e.g. flood protection, navigation, water supply, transportation, etc.).

Hydrodynamic Model of the CRE

The CH3D model, originally developed by Sheng (1986), is a non-orthogonal curvilinear grid model capable of simulating complicated hydrodynamic processes including wind driven, density driven, and tidal circulation. The model has a robust turbulence closure scheme for accurate simulation of stratified flows in estuaries and coastal waters (Sheng 1986, 1987, Sheng and Villaret 1989). The non-orthogonal nature of the model enables it to represent the complex geometry of a tidal estuary such as the CRE. The model includes a circulation model to simulate three-dimensional hydrodynamics and a salinity model to simulate salt transport. The model is driven by external forcing prescribed at the boundaries including tidal forcing at the ocean boundary, freshwater inflow from the watershed, and meteorological forcing including wind and rainfall. The CH3D model has been successfully applied to many waterbodies including east coast Florida estuaries such as the Indian River Lagoon, St. Lucie Estuary (Sun 2009), and Loxahatchee River Estuary (Sun 2004).

The Caloosahatchee Estuary CH3D model was developed from the Charlotte Harbor CH3D model (Sheng 2002). The original Charlotte Harbor model was calibrated using two months of hydrodynamic and salinity data collected during summer at six stations located in and around Pine Island Sound and the Peace River. SFWMD extended the model to the CRE using 16 months of continuous monitoring data (Qiu 2002, SFWMD 2003). The Caloosahatchee Estuary CH3D model was further calibrated with three years of salinity observations (October 2001–December 2004) at five stations in the estuary for the evaluation of various alternative plans of the Southwest Florida Feasibility Study and the C-43 Reservoir Project (Sheng and Zhang 2006, Qiu 2006, USACE and SFWMD 2010). An external peer review of the model was conducted in 2006 for this application (Qiu 2006). The latest calibration of the model was conducted with data collected up to 2010 at seven locations in the estuary to support the development of the Lake Okeechobee Adaptive Protocols (SFWMD 2010).

The Caloosahatchee Estuary CH3D model domain covers the entire estuarine system, including Caloosahatchee Estuary, Charlotte Harbor, Pine Island Sound, San Carlos Bay, Estero Bay, and the major tributaries, as well as about 30 km offshore in the Gulf of Mexico (**Figure A-5**). The horizontal grid has 166 x 128 elements with 5,266 water cells allowing fine enough resolution to represent the numerous islands, including the two islands constructed as part of the Sanibel Causeway. The higher resolution within the CRE and San Carlos Bay (50–100 m) provides a more detailed representation of the complex shoreline and the navigation channel. Five vertical layers evenly spaced over the water column enable simulation of density stratification within the estuary.

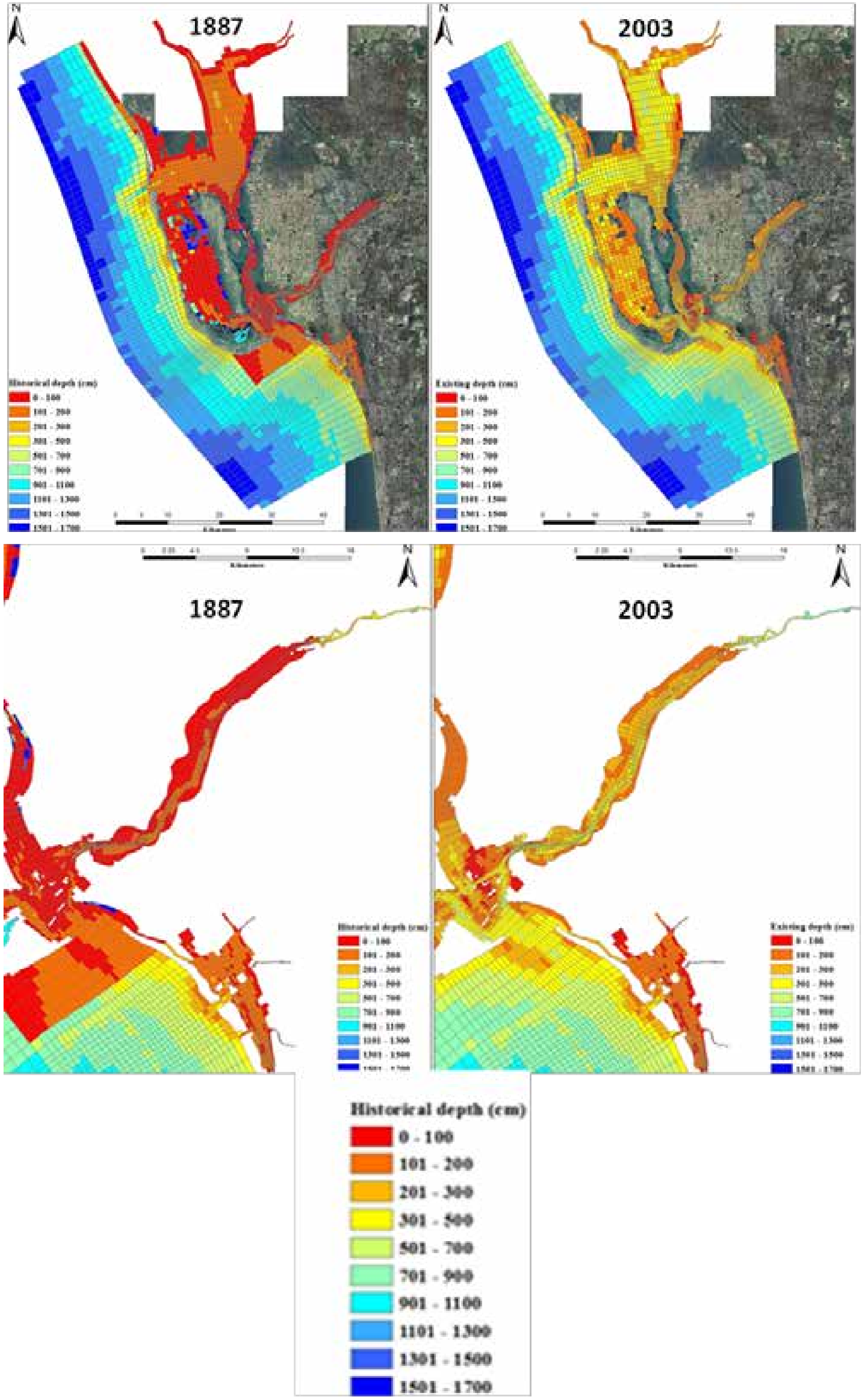


Figure A-5. Comparison of bathymetry of the model domain for the CRE: (top left) the 1887 bathymetry for the entire domain, (bottom left) the 1887 bathymetry focused on the CRE, (top right) the 2003 bathymetry for the entire domain, and (bottom right) the 2003 bathymetry focused on the CRE.

Hydrodynamic Model Experiments

The effects of physical alterations on saltwater intrusion were quantified by comparing the results of altered scenarios with the existing condition under the same boundary forcing. This modeling strategy allowed for isolation of the effects of each physical alteration on salinity patterns. The existing condition was based on bathymetric survey data collected in 2003. Five model experiments were designed to simulate reversals of the historical alterations: (1) removal of S-79 water control structure at the upstream boundary, (2) removal of the Sanibel Causeway at the downstream boundary, (3) backfilling of the oyster bar near Shell Point, (4) filling the navigational channel throughout the estuary, and (5) reestablishing the predevelopment bathymetry from the Captain Black's survey.

The first model experiment investigated the potential effects of removing the S-79 lock and dam on the distribution of salinity in the estuary. To simulate this effect, the model grid was extended from S-79 to S-78. Discharge at S-79 is a combination of discharge at S-78 and runoff from the intervening West Caloosahatchee Subwatershed (**Figure A-4**). Runoff from the watershed was calculated as the difference between discharges at S-79 versus S-78. This simulation applied measured flow at S-78 with the difference between the two discharges redistributed along the C-43 Canal west of S-78.

In the second experiment, the CH3D model grid was modified to eliminate the causeway with its two man-made islands. Estuarine circulation and salinity patterns are heavily influenced by the input of salt water at the downstream boundary. Thus, this scenario simulated the influence of the causeway on salinity within the estuary. Removal of the Sanibel Causeway was implemented by activating the "island" cells of the causeway and assigning them an elevation equal to the average of the submerged neighboring cells (i.e., removal of the two islands).

The effects of the removal of the historical oyster bar were modeled by increasing the elevation of selected areas near Shell Point where historical oyster bars were dredged. This was accomplished by increasing the bottom elevation 0.6 m near the mouth of the CRE. Similarly, the effect of dredging the navigation channel was simulated by changing the elevation of the exiting navigation channel to that of the neighboring cells. The lower CRE and the majority of San Carlos Bay and Pine Island Sound were significantly shallower historically, mostly < 1.5 m in depth, compared to ~2 to 5 m deep in the present existing condition (**Figure A-5**). The increase in depth was apparently due to the dredging of navigational channels including the Intracoastal Waterway. This was done by changing the channel depths in the CH3D model grid from the mouth to S-79 to a maximum of 1.5 m.

The final hydrodynamic model experiment incorporated the bathymetric survey data generated by Captain Black into the existing model grid to represent the predevelopment condition. Historical bathymetry from Captain Black's 1887 survey was interpolated to the modified model grid, which was extended to the S-78 structure (**Figure A-5**). Similar to the S-79 removal scenario, freshwater inflow was applied at the location of S-78 and distributed along the river between S-79 and S-78 with the same total freshwater inflow as the existing condition.

The model was calibrated using data from October 1, 2001, to December 31, 2011 (11 years or 3,744 days). For each run, predicted salinities at the Ft. Myers station and I-75 were compared to those from the existing condition to examine the impact from the change. These two locations were selected for their proximity to the existing MFL compliance monitoring point and monitoring associated with the implementation of the most recent operational schedule.

The existing boundary conditions including tidal water levels, freshwater inflow, and meteorological forcing remained the same for all model scenarios. Tidal data collected at a National Oceanic and Atmospheric Administration (NOAA) station located in Naples, Florida, were used as the ocean boundary condition. The upstream boundary condition resulted from measured freshwater inflow at the S-79 structure available from the SFWMD's corporate environmental database, DBHYDRO (access the database using my.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu) and predicted inflow from tributaries in the Tidal Basin downstream of S-79 (Konya and Wan 2011).

Freshwater inflow through the S-79 structure and the Tidal Basin exhibited significant interannual, seasonal, and daily variations during the simulation period. The surface boundary condition was driven by wind and rainfall/evaporation data available from DBHYDRO. Incoming fresh water at the upstream boundary was assigned a salinity of 0.0 while salinity at the downstream boundary was set at constant value of 35.0. Salinity time series observed at the monitoring stations located along the length of the estuary were interpolated over the model domain to serve as the initial condition. Three years of tidal discharge data (October 2007–September 2010) measured at the two transects at Shell Point and Marker 52 (**Figure A-6**) provided a validation of the sum of tidal flow and freshwater discharge (**Figure A-7**). Water levels were recorded at some of these stations. During the simulation, the Manning's bottom friction coefficient was held constant at 0.025 (Qiu 2006).

Figure A-6. Salinity and inflow monitoring stations in the CRE used for model validation. (Note: Both freshwater inflow and salinity are monitored at the S-79 structure.)

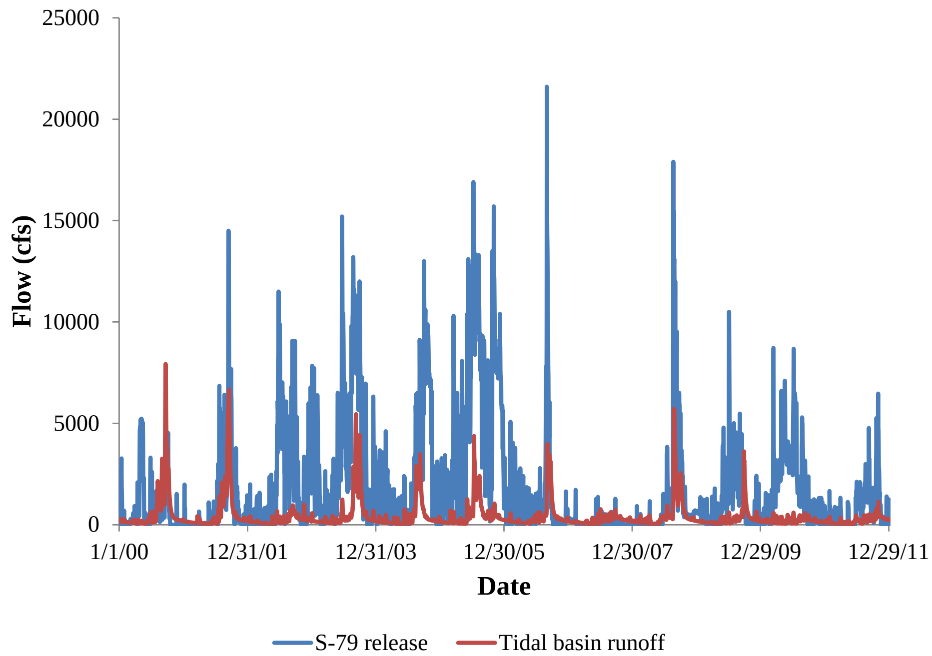


Figure A-7. Freshwater inflow (cfs) from S-79 (blue) and the tidal basin downstream of S-79 (red).

Validation of the existing condition involved long-term data for water level and salinity along with more recent tidal discharge data determined along two transects in the estuary. Seven continuous salinity monitoring stations maintained by SFWMD, including S-79, BR-31, I-75, Ft. Myers, Cape Coral, Shell Point, and Sanibel, provided hourly and daily data for salinity validation (**Figure A-6**). Salinity is measured at two depths: surface (defined at 20% of the total depth below surface) and bottom (defined as 20% of the total depth above the bottom). Hourly salinity data and model results for the same five-year period were compared at five stations: S-79, BR-31, I-75, Ft. Myers, and Shell Point.

Results

Validation of the Existing Condition

The modeled tidal water surface elevation was compared to measured water elevations at four locations: S-79, I-75, Shell Point, and Sanibel Causeway (**Figure A-8**). Only two months (March and April 2010) were presented. Overall, predicted water levels agreed with the measurement at all the four sites in terms of tidal range, tidal phase, and subtidal movement. The root mean square (RMS) error and correlation coefficient (r) along with the relative error defined by the RMS error divided by the average tidal range were calculated from the model results and the field observations over a five-year period (2007 to 2011; **Table A-3**). Despite the relatively larger RMS error at Shell Point due to a small datum offset observed at that location, the RMS errors were within 15% of average tidal range. One possible source of error is the long open tidal boundary in the Gulf of Mexico where only tidal information at Naples was provided. Tidal range in the upper estuary (S-79 and BR-31) was slightly over-predicted possibly due to inadequate representation of the shoreline, floodplain, and bathymetry in this part of the estuary.

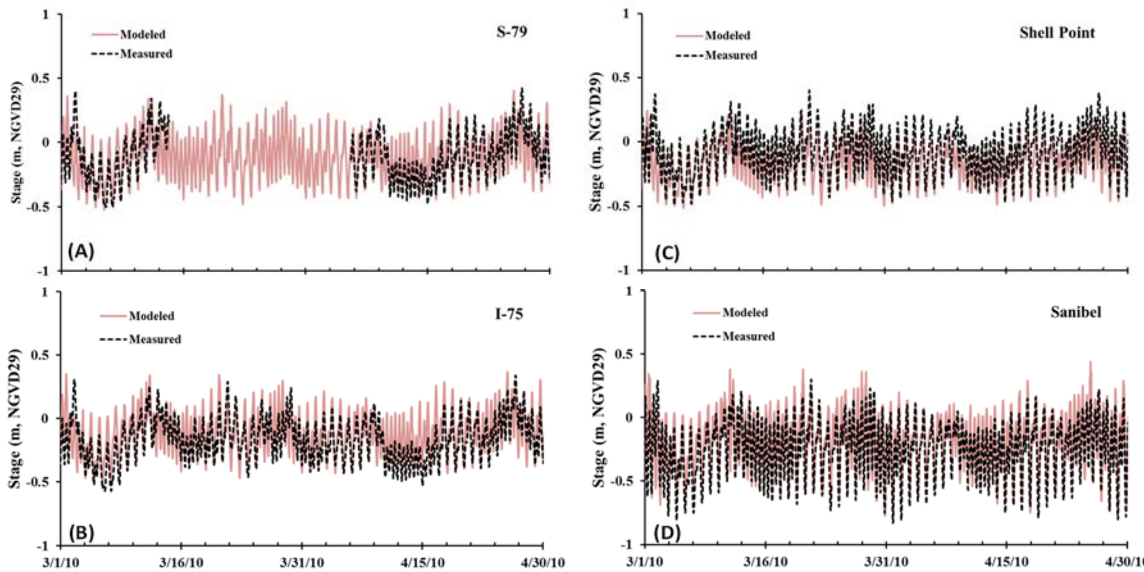


Figure A-8. Modeled (red line) and measured (black dash) tidal elevations at (A) S-79, (B) I-75, (C) Shell Point, and (D) Sanibel Island from March to April 2011.

Table A-3. Model performance statistics for hourly tidal elevation calculated over the period 2007 to 2011.

Station	R^2	RMS Error (m)	Relative Error
S-79	0.74	0.11	12.3%
I-75	0.77	0.12	12.5%
Shell Point	0.83	0.15	15%
Sanibel	0.88	0.10	10%

The discharge at Shell Point is due to the combined contribution determined along three subtransects, which in sum account for the total discharge at the mouth of the estuary (**Figure A-9**). This total discharge was much larger than that at Marker 52 located about 20 km upstream near Fort Myers. The tidal component was dominant relative to the freshwater inflow at the two downstream transects. Model representation of tidal transport agreed with the empirical observations (**Table A-4**).

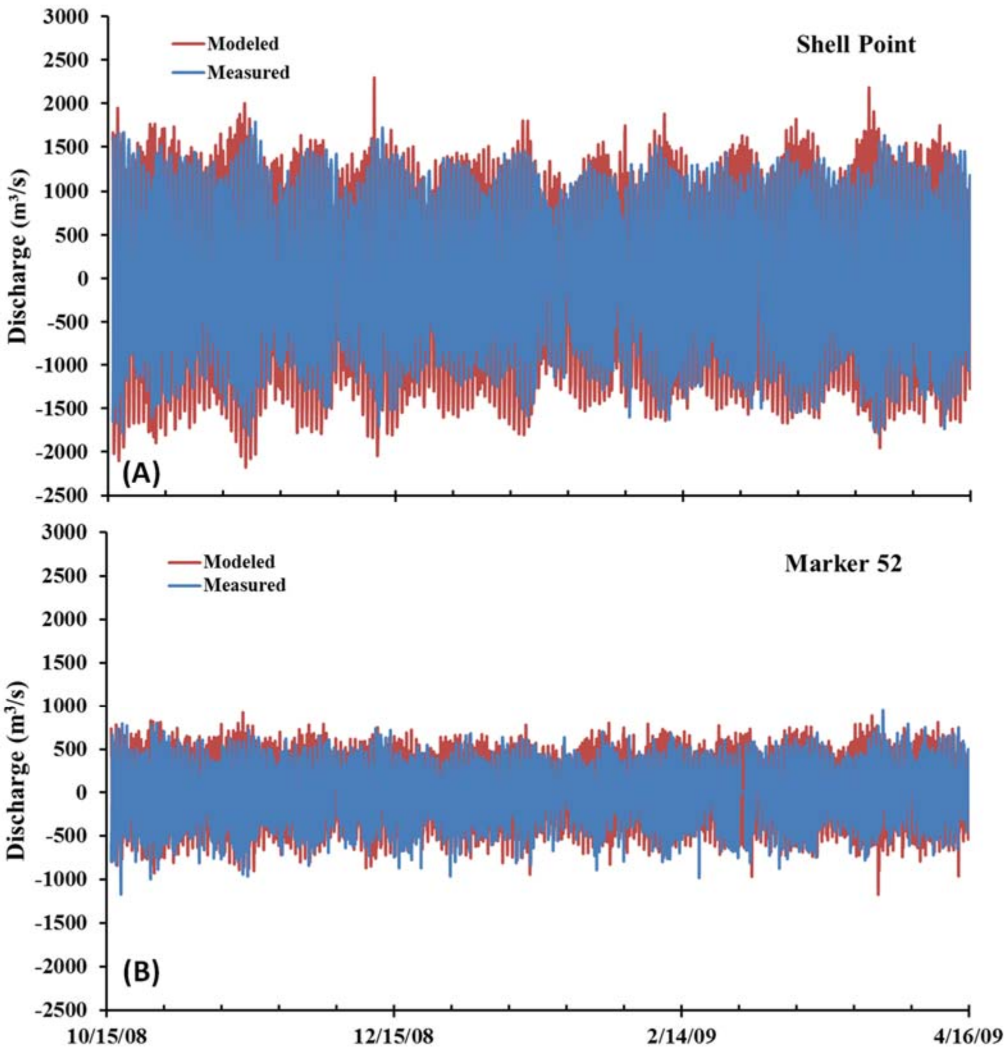


Figure A-9. Modeled (red line) and measured (blue line) tidal discharge at (A) Shell Point, and (B) Marker 52 from October 15, 2008, to April 15, 2009.

Table A-4. Model performance statistics for hourly and daily flow calculated over the period from 2007 to 2011 and from 2001 to 2011, respectively. (Note: $m^3 s^{-1}$ – cubic meters per second.)

Station	R^2	RMS Error ($m^3 s^{-1}$)	Relative Error
Shell point	0.67	446	17.3%
Marker 52	0.72	221	18.1%

Salinities predicted using the model agreed to the hourly data from 2010 (I-75, Ft. Myers, and Shell Point; **Figure A-10**), and, the daily data for the entire period (S-79 and Ft. Myers; **Figure A-11**). This included good representation of fine-scale variations (e.g. stratification), daily variability, and seasonal patterns. Simulation of short-term (daily or in the order of a few days) salinity fluctuations was more reliable at downstream sites (Shell Point and Ft. Myers) than at upstream sites (S-79 and BR-31). This was possibly due to a damping effect inherent in the modeling transport scheme. There was little difference (r = 0.9; RMS 2.5–3.5) between hourly salinities predicted by the model and those measured from 2007 to 2011 (**Table A-5**). The reliability of the salinity prediction was greater at the daily time scale at all locations. These results suggest that the model is a reliable tool for salinity prediction to support decision making regarding water management operations for the CRE.

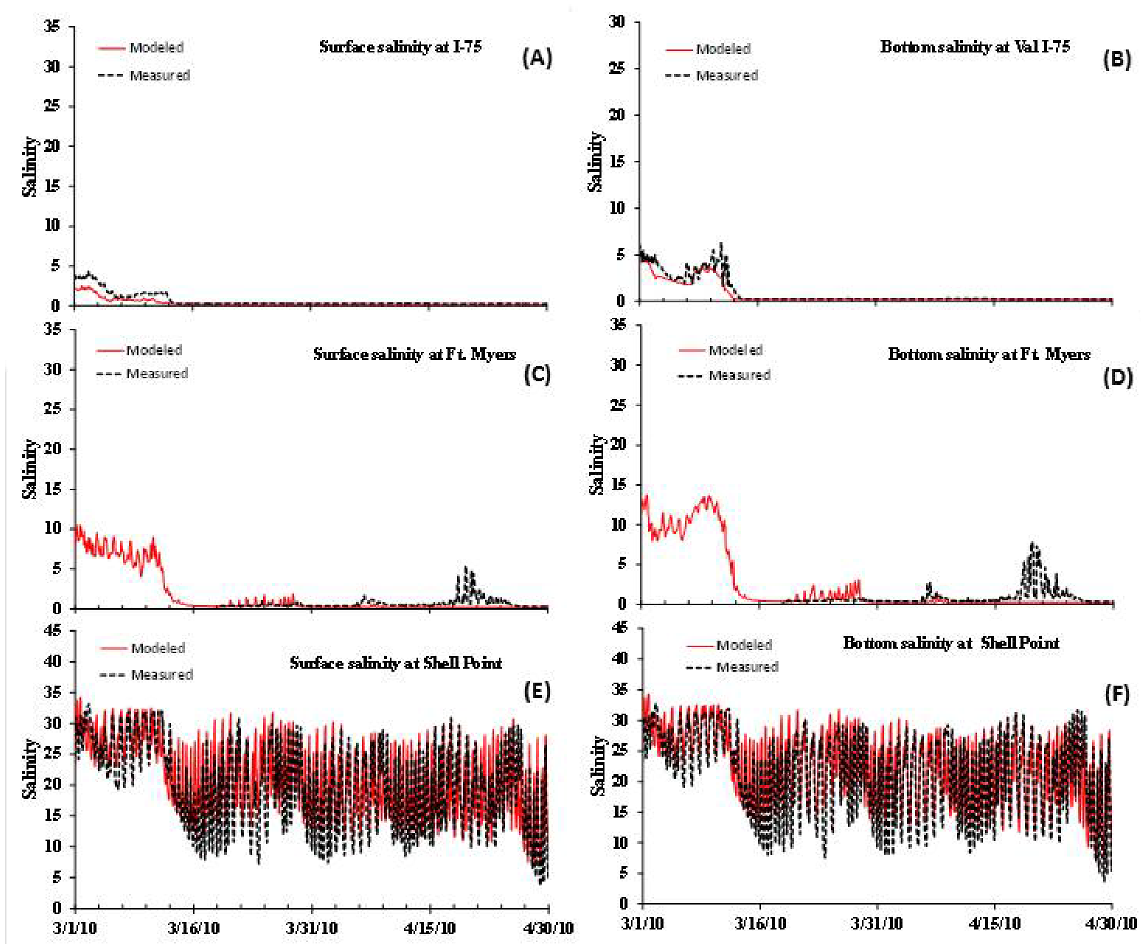


Figure A-10. Modeled (red line) and measured (black dash) hourly surface and bottom salinity at I-75 (A and B), Ft. Myers (C and D), and Shell Point (E and F) from March to April 2010.

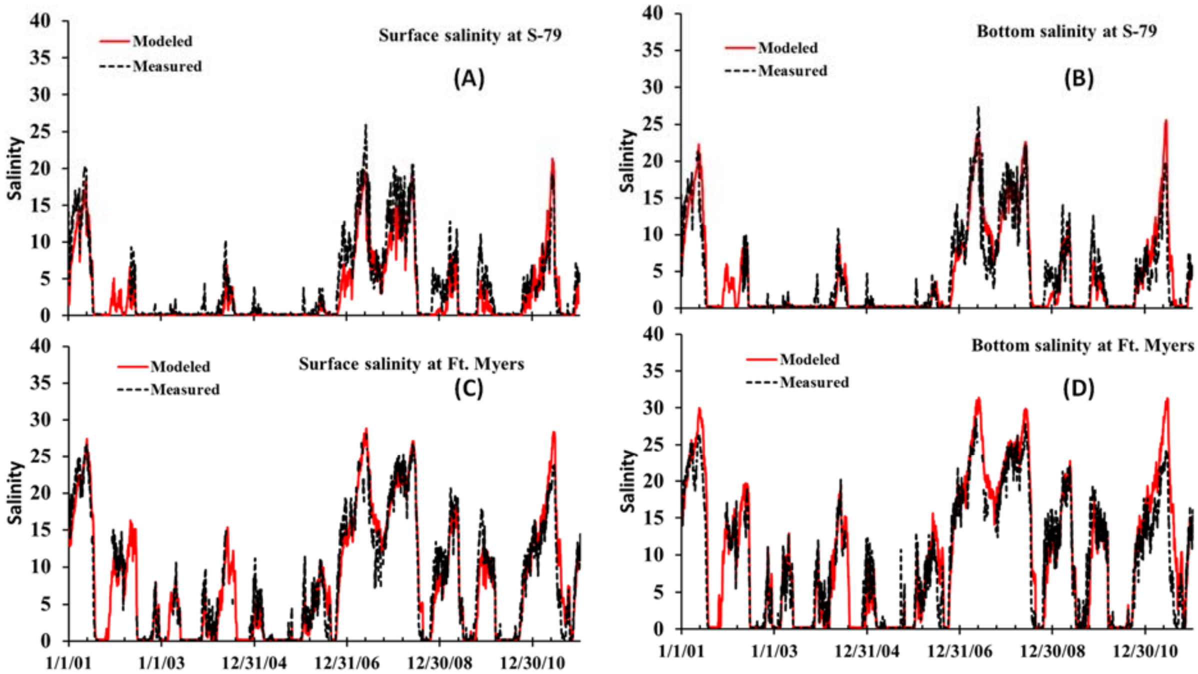


Figure A-11. Modeled (red line) and measured (black dash) daily surface and bottom salinity at S-79 (A and B) and Ft. Myers (C and D) from 2001 to 2010.

Table A-5. Model performance statistics for hourly and daily salinity calculated over the period from 2007 to 2011 and from 2001 to 2011, respectively.

Station	Hourly (2007 to 2011)				Daily (2001 to 2011)			
	Surface		Bottom		Surface		Bottom	
	R^2	RMS	R^2	RMS	R^2	RMS	R^2	RMS
S-79	0.85	2.68	0.85	3.27	0.88	2.17	0.86	2.25
BR-31	0.88	2.44	0.81	3.41	0.90	1.91	0.83	2.65
I-75	0.88	2.32	0.93	2.91	0.88	2.27	0.86	2.87
Ft. Myers	0.88	3.22	0.85	5.11	0.92	2.31	0.88	2.98
Cape Coral					0.94	2.46	0.94	2.95
Shell Point	0.79	3.58	0.77	3.79	0.88	2.78	0.85	2.90
Sanibel					0.7184	2.03	0.74	2.80

Hydrodynamic Model Experiments

The total freshwater inflow entering the CRE was the same between the existing condition and the scenario where S-79 was removed. Salinity decreased slightly during the dry season without the control structure at the estuary head (**Figure A-12A**). The relative difference in salinity was greater at I-75 (not shown) than at the Ft. Myers station with a more noticeable deviation in the bottom water. Salinity at Ft. Myers did not change significantly with the removal of the Sanibel Causeway (**Figure A-12B**). However, there was a slight increase in salinity at Sanibel during the dry season (data not shown). While dry season salinity at Ft. Myers increased slightly when the oyster bar was reestablished, this effect diminished in the upstream direction (**Figure A-12C**). In contrast, filling the navigational channel led to reductions in salinity throughout the CRE during the dry season (**Figure A-12D**). Finally, reintroduction of the predevelopment bathymetry resulted in significantly lower salinity in upstream regions of the estuary relative to the existing condition (**Figure A-12E**). Except for the four drought years (2001, 2007, 2008, and 2011), the estuary would be nearly fresh upstream of the Ft. Myers station even during the dry season. Changes in both average surface and bottom salinities at I-75 and Ft. Myers were most pronounced in the scenarios that decreased the depth of the navigational channel or across the entire model grid (**Table A-6**).

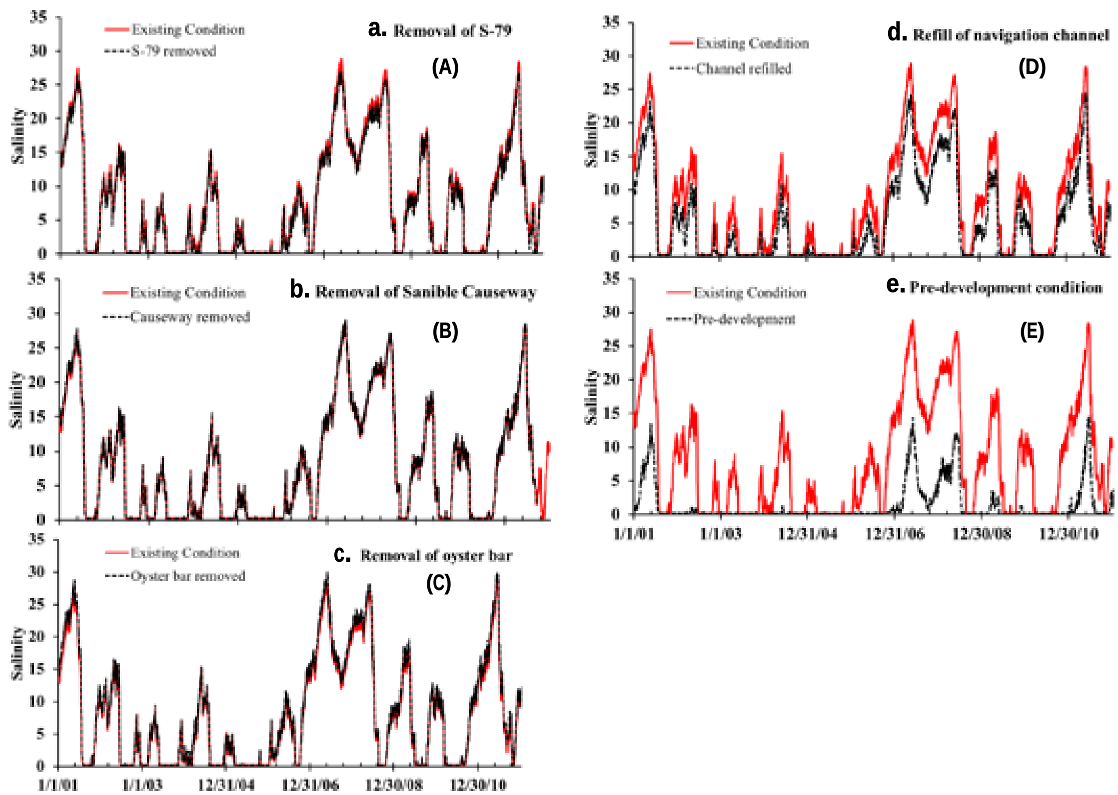


Figure A-12. Comparison between average daily surface salinity at Ft. Myers (red line) and five different physical alteration experiments (black dash) from 2001 to 2010: (A) removal of S-79; (B) removal of Sanibel Causeway; (C) restoration of oyster bar at the mouth; (D) refill of the navigational channel; and (E) reestablishment of predevelopment bathymetry.

Table A-6. Difference of monthly average surface (S) and bottom (B) salinity between each experiment and the existing condition at I-75 and Ft. Myers in May 2001, 2007, 2008, and 2011.

Scenario		2001		2007		2008		2011	
		I-75	Ft. Myers	I-75	Ft. Myers	I-75	Ft. Myers	I-75	Ft. Myers
S-79 Removal	S	-1.03	-0.84	-2.57	-1.49	-1.61	-1.04	-1.54	-0.95
	B	-2.56	-1.31	-3.27	-1.88	-2.59	-1.40	-2.62	1.59
Causeway Removal	S	0.14	0.15	0.16	0.16	0.12	0.14	0.15	0.17
	B	0.15	0.18	0.17	0.16	0.13	0.14	0.16	0.16
Restore Oyster Bar	S	0.75	0.49	1.33	0.95	1.38	1.02	1.46	1.02
	B	1.01	1.23	1.39	1.33	1.46	1.37	1.56	1.56
Refill Navigation Channel	S	-5.7	-4.5	-5.5	-4.5	-5.7	-5.0	-5.6	-4.7
	B	-4.8	-4.8	-5.1	-4.9	-5.7	-5.4	-5.0	-5.1
Predevelopment	S	-14.4	-14.8	-17.1	-15.3	-15.9	-14.1	-14.7	-14.7
	B	-15.4	-14.2	-19.1	-16.2	-17.9	-17.9	-17.4	-16.4

Theoretical Considerations for Salt Intrusion

In many estuaries, reduced freshwater inflow over time can result in landward salinity encroachment (Cloern and Jassby 2012). There have been many attempts to address the problem based on theoretical and experimental approaches. With a prismatic channel, analytical solutions of salt transport equations have been given by various authors (Ippen and Harleman 1961, Ippen 1966, Prandle 1985, 2004, 2009, Savenjie 1992, 2005, Kuijper and Van Rijn 2011). When averaged on tidal time scales, the one-dimensional salt continuity equation can be simplified to a balance between the seaward advective salt transport and the landward dispersive transport (Savenije 2005):

$$u_r S + D_x \frac{dS}{dx} = 0 \qquad \textbf{\textit{A.1}}$$

Where x is the distance from the mouth, u_r is the river discharge velocity, S is salinity, and D_x is the dispersive coefficient. Each parameter was averaged over multiple tidal cycles and the channel cross-sectional area. The transport due to advection is caused by the velocity associated with freshwater discharge, whereas the longitudinal dispersive transport is caused by tidally- and density-driven processes. Longitudinal dispersion in estuaries can be particularly difficult to measure and model (Jay et al. 1997, Austin 2004, Geyer et al. 2008, Spencer et al. 2014). Nevertheless, the theory can still provide qualitative guidance.

The most important parameters influencing salt intrusion are the tidal characteristics (tidal amplitude and peak tidal velocity), river parameters (discharge and average cross-sectional velocity), and geometric parameters (depth, width, and convergence length scale). Using a tidally averaged approach and assuming the following relation between the dispersion coefficient D_x and river discharge velocity u_r (Van Der Burgh 1972) results in **Equation A-2**:

$$\frac{dD_x}{dx} = -Ku_r \qquad \textbf{\textit{A.2}}$$

where K is a calibration coefficient (Van Der Burgh coefficient) between 0 and 1. The salt balance equation can be solved and the maximum salt intrusion length L_{max} (defined as the salt penetration length at high slack water) can be expressed as **Equation 3** (Savenije 2005, Kuijper and Van Rijn 2011):

$$L_{max} = L_a \ln\left(1 + \frac{D_0 A_0}{K L_a Q_r}\right) \qquad \textbf{\textit{A.3}}$$

where L_a is the convergent length scale for the cross-section area $A = A_0\exp(-x/L_a)$, A_0 is the cross-section area at the mouth, D_0 is the dispersive coefficient at the mouth, and Q_r is the river discharge. For prismatic estuaries, **Equation A-3** is reduced to the following:

$$L_{max} = \frac{D_0 A_0}{K Q_r} \qquad \textbf{A.4}$$

Savenije (2005) also found an empirical relationship for the dispersive coefficient at the mouth:

$$D_0 \sim 1400 \widehat{u_0} h_0 \qquad \textbf{A.5}$$

where $\hat{u}_0$ is the peak tidal velocity and h_0 is the depth at the mouth.

Thus, it is evident from **Equations A-3** through **A-5** that salt intrusion length would increase significantly with increasing depth h and cross-section area A. This theoretical consideration is consistent with the numerical simulation results of the last two of scenarios of physical alteration (e.g. refilling the estuarine channel and return to the predevelopment bathymetry).

Discussion

This study applied a three-dimensional, curvilinear hydrodynamic model (CH3D) to investigate the impact of physical alterations on salinity in the CRE. Simulated salinity distributions and time series from five different model experiments representing physical alterations to the estuary were compared to those from the existing condition. Intra- and interannual variations in the model's existing salinity conditions were validated using extensive data collected from 2000 to 2011. With all forcing being kept the same, the modeled salinity of the existing conditions was compared with five cases in which historical physical alterations of the estuary were reversed, including (1) removal of the S-79 structure, (2) removal of the Sanibel Causeway, (3) backfill of the oyster bar, (4) backfill of the navigation channel, and (5) predevelopment bathymetry.

Model results indicated that the construction of the Sanibel Causeway, the removal of the oyster bar near the estuarine mouth, and the S-79 water control structure had little effect on salinity of the CRE. Potential effects of these alterations were localized and spatially limited. In contrast, dredging the navigational channels greatly increased salinities throughout the estuary. Under the predevelopment bathymetry, before dredging, salinity was dramatically lower in the estuary upstream of Fort Myers being nearly fresh in the dry season except for the drought years of 2001, 2007, 2008, and 2011. Dredging and deepening of the estuary was one of the primary activities that changed the pattern of salt transport in the estuary. This is consistent with the analytical theory about the significance of estuary depth and cross-sectional area in salt intrusion. There are two factors that could explain this difference. On the one hand, refilling the channel provided more resistance to salt intrusion; on the other hand, the volume of the estuary was significantly reduced, but the amount of freshwater input remained the same, resulting in reduced salinity in the estuary. Since these physical changes are unlikely to be reversed, the results may have important implications in the development of realistic inflow goals to protect the estuarine ecosystem. This modeling evaluation provides a framework for understanding the influence of different structural alterations on resulting salinity distributions. It should be recognized that these irreversible alterations act as constraints on the ability to restore historical hydrologic conditions to the CRE.

Component Study 2: Analysis of the Relationship between Freshwater Inflow at S-79 and Salinity in the CRE 1993–2013

Christopher Buzzelli

Abstract

The upstream migration of salt with reduced freshwater inflow alters the composition and productivity of oligohaline habitats in estuaries. This process can be problematic in subtropical estuaries with regulated freshwater inflow such as the CRE in southwestern Florida. This study component examined relationships between average monthly inflow (Q) and mid-estuary salinity (S) from 1993 to 2013. An exponential decay equation was fit to the inflow-salinity (Q-S) relationship for each water year (May 1 to April 30). Annual equations were used to estimate the inflow rate associated with a salinity of 10 at the Ft. Myers monitoring station (Q_{calc}). Inflows varied both intra- and interannually. Q_{calc} ranged from 70 cfs to 773 cfs with an average of 445 ± 218 cfs. At the estuary and annual scales, the quantity of fresh water to support a particular salinity target varied greatly. This variance was related to the variations in freshwater inputs from both the C-43 Watershed located upstream of S-79 structure and the downstream Tidal Basin.

Introduction

Life histories of many estuarine organisms are directly dependent upon temporal and spatial variations in salinity (Livingston et al. 1997, Palmer et al. 2011, Whitfield et al. 2012). The vertical and horizontal patterns of salinity can be quantified using lines of equal salinity (e.g. isohalines) whose positions fluctuate with freshwater inflow, tidal cycles, and meteorological phenomena (e.g. fronts, winds, and storms; Jassby et al. 1995). Upstream or downstream shifts in isohaline position can narrow the optimal habitat for estuarine organisms or move them further away from their optimal locations (Sklar and Browder 1998). Data analyses and research to provide guidelines for freshwater management should rely upon appropriate physical and ecological indicators and seek clear breakpoints in relationships between inflow, salinity, and biological responses (Montagna et al. 2002a). Therefore, isohaline position can be used as an indicator of ecological conditions in estuaries (Jassby et al. 1995).

The CRE has a watershed characterized by extensive agriculture and urbanization, is influenced by freshwater inflow from several sources, and contains valuable biological resources (Chamberlain and Doering 1998a, Doering et al. 2006, Balci and Bertolotti 2012). Through combinations of climatic variations, landscape modification, and managed operations, the CRE can experience variable freshwater inflow during the dry season. In many estuaries reduced freshwater inflow over time can result in the landward encroachment of salinity (Cloern and Jassby 2012). In the case of the CRE, upstream salt migration can reduce the extent of vegetated freshwater habitat (i.e., *Vallisneria americana*), impact community composition in the water column and benthos, and compress the oligohaline area of the estuary essential to a variety of faunal populations (Doering et al. 2002, Simpfendorfer et al. 2011, Palmer et al. 2011, Stevens et al. 2013).

Continuous salinity recorders have been in place near Fort Myers, Florida since 1992. The objective of this study was to quantify interannual variations in the estimated freshwater inflow from S-79 associated with a salinity of 10 (S_{10}) at the Ft. Myers station.

Methods

This analysis focused on the average daily freshwater inflow at S-79 (Q_{S79}) and did not consider freshwater inputs from tributaries or groundwater downstream of S-79. Inflows from January 1, 1992, to May 1, 2013, were downloaded from DBHYDRO, which can be accessed at my.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu. Average daily salinity determined at the Ft. Myers station (S_{FtM}) over the same period of record (POR) was downloaded and combined with the inflow data. The two data sets were used to generate a time series of average monthly values (**Figure A-13A**). The overall relationship between average monthly inflow (Q_{S79}) and average monthly salinity at Ft. Myers (S_{FtM}) follows a negative exponential form (**Figure A-13**; Qiu and Wan 2013):

$$S_{FtM} = a * e^{(-b * Q_{S79})} \qquad \textbf{\textit{A.6}}$$

The average monthly inflow and salinities were categorized by water year to derive 21 individual years of coupled inflow-salinity records (n = 12 per water year). Evaluation of monthly average inflows and salinities provides the appropriate scale for interannual comparisons and eliminates the concern for finer scale transport processes (days-weeks). Scatter plots similar to **Figure A-13**B were generated for each water year (**Figure 14A-U**). The negative exponential curve fit to the scatter plots for each year resulted in estimates of the degree of fit (r^2) and two equation parameters (a, b) to calculate salinity at the Ft. Myers station. There were five water years for which the relationship was unusable. The high inflows throughout WY1995 resulted in average monthly salinities < 5. Inflow and salinities in the dry (November–April) and wet (May–October) seasons were anomalous in WY2006 as tropical storms in 2005 led to extreme freshwater releases from Lake Okeechobee from late 2005 to mid 2006 (**Figure A-13**A). Precipitous decreases to inflow in WY2007 due to drought rendered the curve-fitting procedure meaningless. Similarly, the greatly reduced inflow and exacerbated salinity in WY2008 resulted in an uncertain mathematical relationship. Finally, the salinity sensor was unavailable for several months in WY2010. The negative exponential equation for each of the remaining 16 water years was solved to predict Q_{S79} required for S_{10} (Q_{calc}):

$$Q_{calc} = \frac{\ln(S_{10}) - \ln(a)}{-b} \qquad \textbf{\textit{A.7}}$$

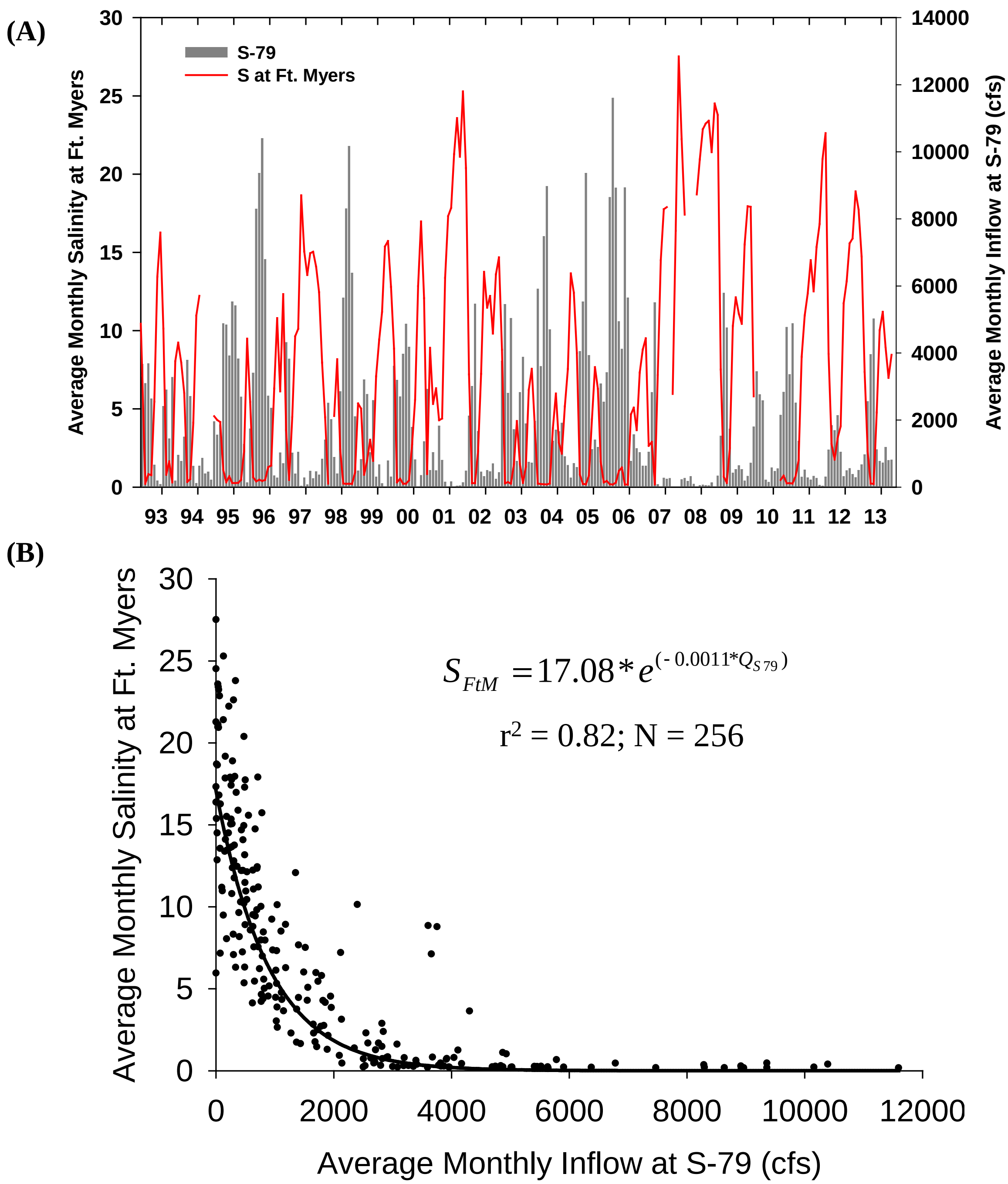


Figure A-13. (A) Time series of average monthly inflow from the S-79 structure to the CRE and average monthly salinity at the Ft. Myers monitoring station. (B) Negative relationship between inflow (Q_{S79}) and salinity (S_{FtM}) represented by an exponential decay equation. (Note: All months from the POR, WY1993–WY2013, are included.)

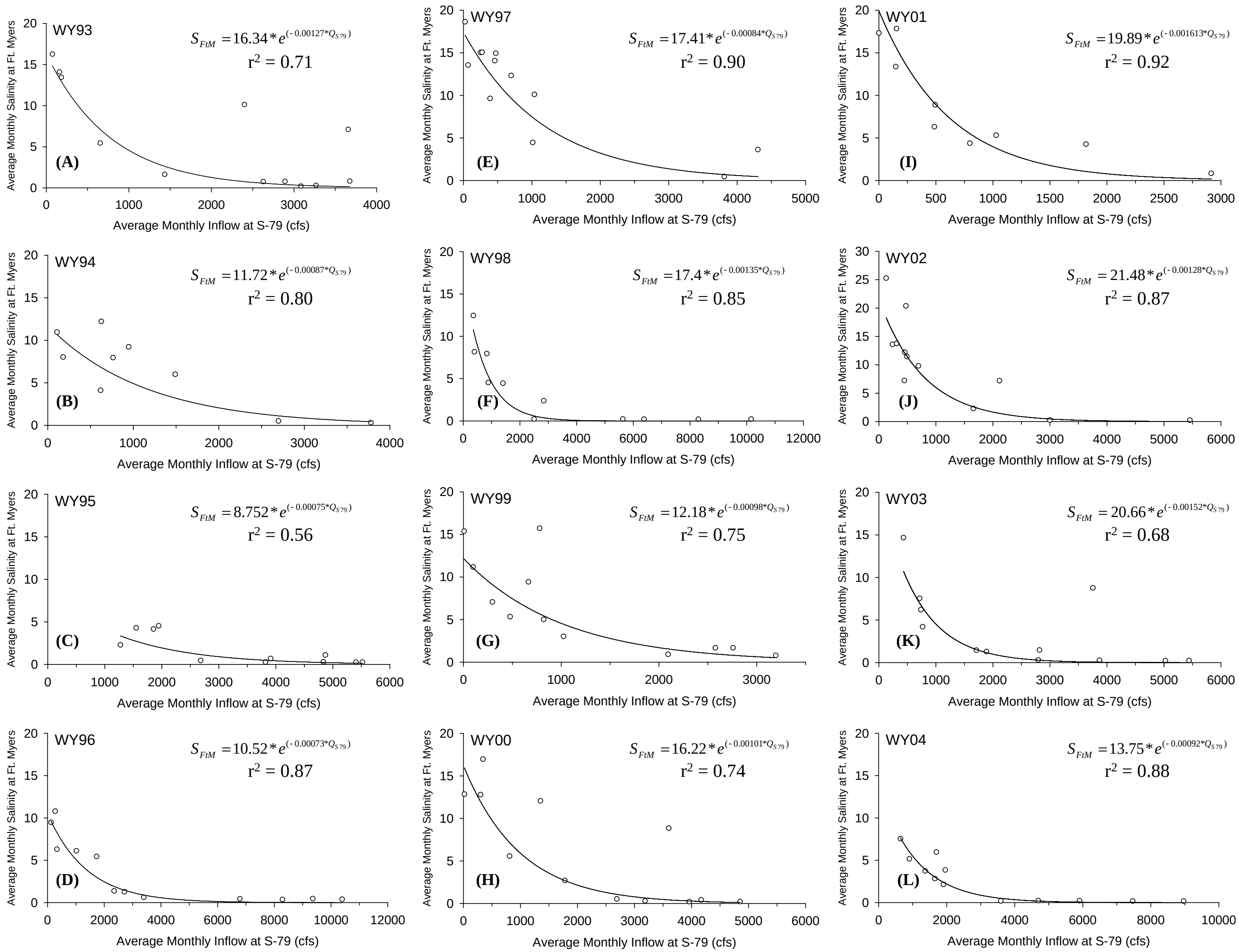


Figure A-14A–U. Series of scatter plots and fitted exponential decay equations between average monthly inflow at S-79 (cfs) and average monthly salinity at the Ft. Myers monitoring station since WY1993.

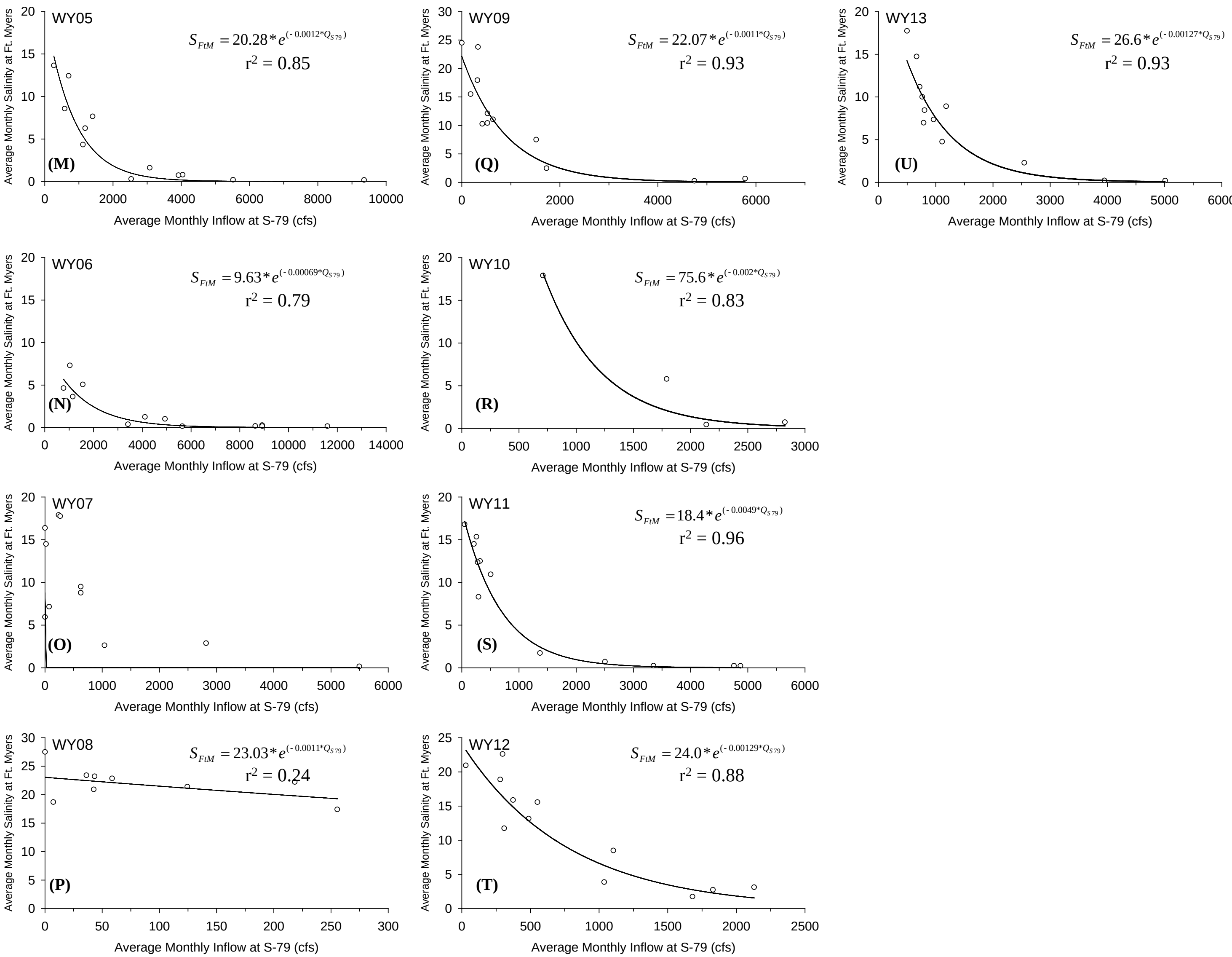


Figure A-14A-U. Continued.

Results

Average monthly inflows varied both intra- and interannually from WY1993 to WY2013 (**Figures A-14A** through **A-14U**). As noted, inflows were extremely low (< 300 cfs) in WY2008 (**Figure A-14P**). The maximum monthly inflows were comparatively low in WY1993 (1,997 cfs), WY1994 (1,073 cfs), WY1997 (1,069 cfs), WY1999 (1,238 cfs), WY2000 (2,256 cfs), WY2001 (664 cfs), WY2002 (1,291 cfs), WY2003 (2,500 cfs), WY2009 (1,397 cfs), WY2011 (1,576 cfs), and WY2013 (1,585 cfs; **Table A-7**). Average monthly salinity at the Ft. Myers station ranged from 5.5 to 11.0 among these years. By contrast, average monthly inflows were comparatively high in WY1996 (3,905 cfs), WY1998 (3,445 cfs), WY2004 (3,394 cfs), WY2005 (2,817 cfs), and WY2006 (5,074 cfs; **Table A-7**). Average monthly salinities were 3.9, 3.8, 2.7, 5.1, and 2.0, respectively, for these water years under comparatively higher freshwater inflow.

Table A-7. Summary from analysis of average monthly inflow at S-79 (Q_{S79}) and average monthly salinity at Ft. Myers (S_{FtM}). (Notes: An exponential decay curve was used to describe the relationship between the average monthly values for each water year. Table values for each water year include the average inflow [Q_{S79}] and salinity at Ft. Myers [S_{FtM}], curve fit parameters [r^2, a, and b], and the calculated inflow to achieve a salinity of 10 at Ft. Myers [Q_I].)

Water Year	Q_{S79} (cfs)	S_{FtM}	r^2	a	b	Q_I (cfs)
1993	1,997	5.5	0.71	16.34	0.00127	386
1994	1,073	7.0	0.80	11.72	0.00087	183
1995	3,152	1.4				
1996	3,905	3.9	0.87	10.52	0.00073	70
1997	1,069	11.0	0.90	17.41	0.00084	657
1998	3,445	3.8	0.85	17.40	0.00135	410
1999	1,238	6.4	0.75	12.18	0.00098	201
2000	2,256	6.1	0.74	16.22	0.00101	479
2001	664	12.0	0.92	19.89	0.00161	426
2002	1,291	10.3	0.87	21.48	0.00128	597
2003	2,500	3.9	0.68	20.66	0.00152	477
2004	3,394	2.7	0.88	13.75	0.00092	346
2005	2,817	5.1	0.85	20.28	0.00120	589
2006	5,074	2.0				
2007	953	8.8				
2008	113	21.6				
2009	1,397	11.4	0.93	22.07	0.00110	720
2010	1,516	7.5				
2011	1,576	7.8	0.96	18.40	0.00487	125
2012	844	11.6	0.88	24.00	0.00129	677
2013	1,585	7.7	0.93	26.63	0.00127	773
Average	1,993	7.6				445 $\pm$ 218

The degree of fit (r^2) for the relationship between average monthly inflow and average monthly salinity at the Ft. Myers station ranged from 0.71 to 0.96 among 17 water years (**Table A-7**). r^2 was lowest in WY1993 (0.71) and WY2003 (0.68) and greatest in WY2001 (0.92), WY2009 (0.93), WY2011 (0.96), and WY2013 (0.93). Q_{calc} to achieve S_{10} at Ft. Myers ranged from 70 cfs (WY1996) to 773 cfs (WY2013) with an average (± standard deviation) of 445 ± 218 cfs over all water years (**Figure A-15**).

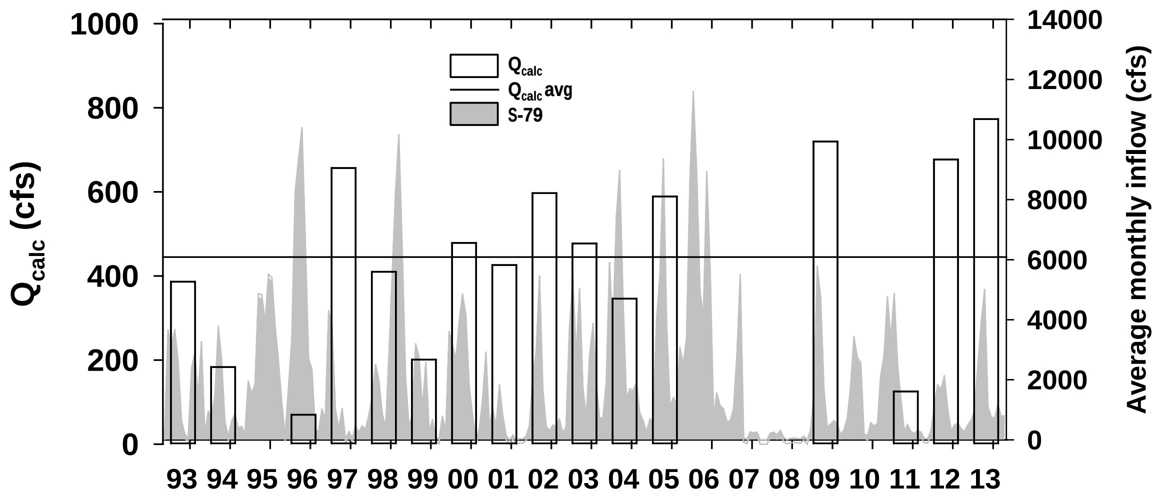


Figure A-15. Time series of the calculated amount of freshwater inflow from S-79 associated with a salinity of 10 at Ft. Myers (Q_{calc}). (Note: The average Q_{calc} is shown [445 cfs].)

Discussion

This study demonstrated that the amount of freshwater inflow at the head of the CRE varies greatly both intra- and interannually. This has implications for attempts to establish inflow requirements to the estuary. The quantity of fresh water delivered from S-79 associated with a salinity target of 10 at the Ft. Myers station varied from 70 to 773 cfs depending upon the contribution from the downstream Tidal Basin. In fact, the amount of ungauged freshwater input from the Tidal Basin is likely to be a key component to the total freshwater budget for the estuary. Modeling of freshwater inputs from tributaries and groundwater in the downstream Tidal Basin is ongoing and these inputs have been incorporated into the CRE CH3D Model (Wan et al. 2013).

Component Study 3: Relationships between Freshwater Inflows and Water Quality Attributes during the Dry Season in CRE

Christopher Buzzelli, Peter Doering, Teresa Coley, and Zhiqiang Chen

Abstract

Decreased flushing with reduced inflow can lead to the deposition of phytoplankton biomass and bottom water hypoxia in estuaries. This study component utilized event-scale water quality data, long-term monitoring of CHL, and simulation modeling of phytoplankton dynamics to evaluate low freshwater inflows that could contribute to water quality problems in the upper CRE. The highest CHL and lowest DO concentrations occur in the upper CRE under low inflows. Although more research is needed, it is hypothesized that dry season inflows of less than approximately 500–600 cfs may promote bottom water hypoxia in the deeper channel of the upper CRE. Field and model results indicated that CHL concentrations greater than the water quality standard of 11 µg L^{-1} were associated with inflows of 469 ± 689 cfs and 269 ± 493 cfs, respectively. Low level inflows (< 500 cfs) need to be further studied to better quantify the discharge required to mitigate the potential for hypoxia in the upper CRE.

Introduction

Bottom water hypoxia (DO concentrations £ 3 milligrams per liter [mg L^{-1}]) is increasingly common in many estuaries (Diaz and Rosenberg 2008, Committee on Environment and Natural Resources 2010). Recurring hypoxia negatively impacts benthic fauna, fish populations, fishery harvest, and ecosystem energy flow (Breitburg 2002, Powers et al. 2005, Diaz and Rosenberg 2008, Rabalais et al. 2010). The potential for bottom water hypoxia is directly related to phytoplankton blooms as phytoplankton detritus stimulates DO consumption below the pycnocline (Paerl et al. 2006, Livingston 2007, Kemp et al. 2009, Committee on Environment and Natural Resources 2010). Processes can be complex due to spatial and temporal lags among hydrodynamic drivers, phytoplankton production and deposition, and bottom water hypoxia.

Relationships between freshwater inflow and phytoplankton production in estuaries are dependent upon the time scales of transport, growth, and grazing (Cloern et al. 2014). Reduced inflow can promote phytoplankton blooms through longer water residence time, decreased vertical mixing, and enhanced light in the surface layer (Lancelot and Muylaert 2011, Wan et al. 2013, Cloern et al. 2014). Anthropogenic factors such as increased water temperature from climate change, reductions in filter feeders, and increased nutrient loads can stimulate phytoplankton production in excess of consumption (Kemp et al. 2009). Phyto-detritus not consumed or transported downstream reaches bottom sediments through vertical settling (Cloern et al. 2014).

Estuarine phytoplankton production can be viewed on annual, seasonal, and event (< 1 month) time scales (Cloern and Jassby 2009). Phytoplankton dynamics at the event-scale can be particularly acute in small estuaries with subtropical climate and managed freshwater inflows (Schlacher et al. 2008, Buzzelli 2011, Azevedo et al. 2014). Phytoplankton responses to pulsed river discharges are sometimes modulated by zooplankton grazing (Wolanski et al. 2004). However, low flow conditions favor phytoplankton growth in excess of loss, upstream migration of the chlorophyll *a* maximum (CHL_{max}), and hypoxia in the upstream bottom water (Schlacher et al. 2008). Upstream encroachment of CHL_{max} is common for microtidal Gulf of Mexico estuaries with subtropical climates and vertical stratification under reduced flushing (Murrell et al. 2007). The CRE possesses many of these characteristics.

Changes to freshwater inflow have altered salinity regimes and the overall ecology of the estuary (Chamberlain and Doering 1998a, Barnes 2005). The CHL_{max} (~30 µg L^{-1}) moves upstream towards the water control structure at the estuarine head (S-79) under low inflows (0–500 cfs; Doering et al. 2006, Tolley et al. 2010, Radabaugh and Peebles 2012, Buzzelli et al. 2014a). When this occurs, the highest CHL and lowest DO concentrations can be coincidently located upstream (Doering and Chamberlain 1998). Like many estuaries, hypoxia develops through increased residence time, reduced vertical mixing, and increased deposition of phyto-detritus (Tolley et al. 2010, Radabaugh and Peebles 2012). This process was particularly evident in 2000 as the CRE experienced a decline in bottom water DO one to two months following a phytoplankton bloom (Doering et al. 2006). Reduced freshwater inflow results in the proliferation of diatoms in the upper CRE (Tolley et al. 2010). While this can stimulate the food web, unconsumed phyto-detritus can contribute to bottom water hypoxia.

There is limited information on the effects of low level freshwater inflows on patterns of salinity and water quality in the CRE. Additionally, it is very difficult to rely on the CHL concentration as an indicator of freshwater inflow. This is because CHL is itself an uncertain indicator of a variety of non-linearly related physical, biogeochemical, and biological processes (Buzzelli 2011, Cloern et al. 2014). The objective of this study component was to consider relationships between freshwater inflows and water quality attributes during the dry season. Of interest were freshwater discharges that position the CHL_{max} in the upper estuary, thus potentially enhancing deposition of phyto-detritus and hypoxic conditions in the bottom waters. This was accomplished through three synergistic approaches. First, fine-scale detection of water quality gradients with managed freshwater inflows (Adaptive Protocol Release Study [APRS]) was applied to better understand patterns at the event scale in the dry season. Second, analysis of long-term monitoring data provided a platform to examine patterns of CHL with intra- and interannual variations in inflow. Finally, a simulation model of phytoplankton dynamics was used to examine CHL patterns with variable transport and material cycling in the upper CRE over a range of scales.

Methods

Adaptive Protocol Release Study

This study presented a unique opportunity to evaluate the potential effects of short-term inflows on water quality and plankton abundances during the dry season. It was unique because it combined the operational capacity to regulate inflow through S-79 with ecological responses along the CRE salinity gradient and rapid in situ data acquisition (e.g. flow-through system; Madden and Day 1992, Lane et al. 2007, Buzzelli et al. 2014a).

The Adaptive Protocol Release Study (APRS) focused on the event scale to assess potential effects of short-term pulses of fresh water on water column ecological attributes along the length of the CRE. A total of 23 APRS research cruises were conducted during in dry seasons (November–April) between January 2012 and April 2014. The cruises utilized a combination of continuous flow-through technology and a series of vertical sampling stations. Cruises covered a total distance of ~42 km from S-79 to San Carlos Bay (**Figure A-16**).

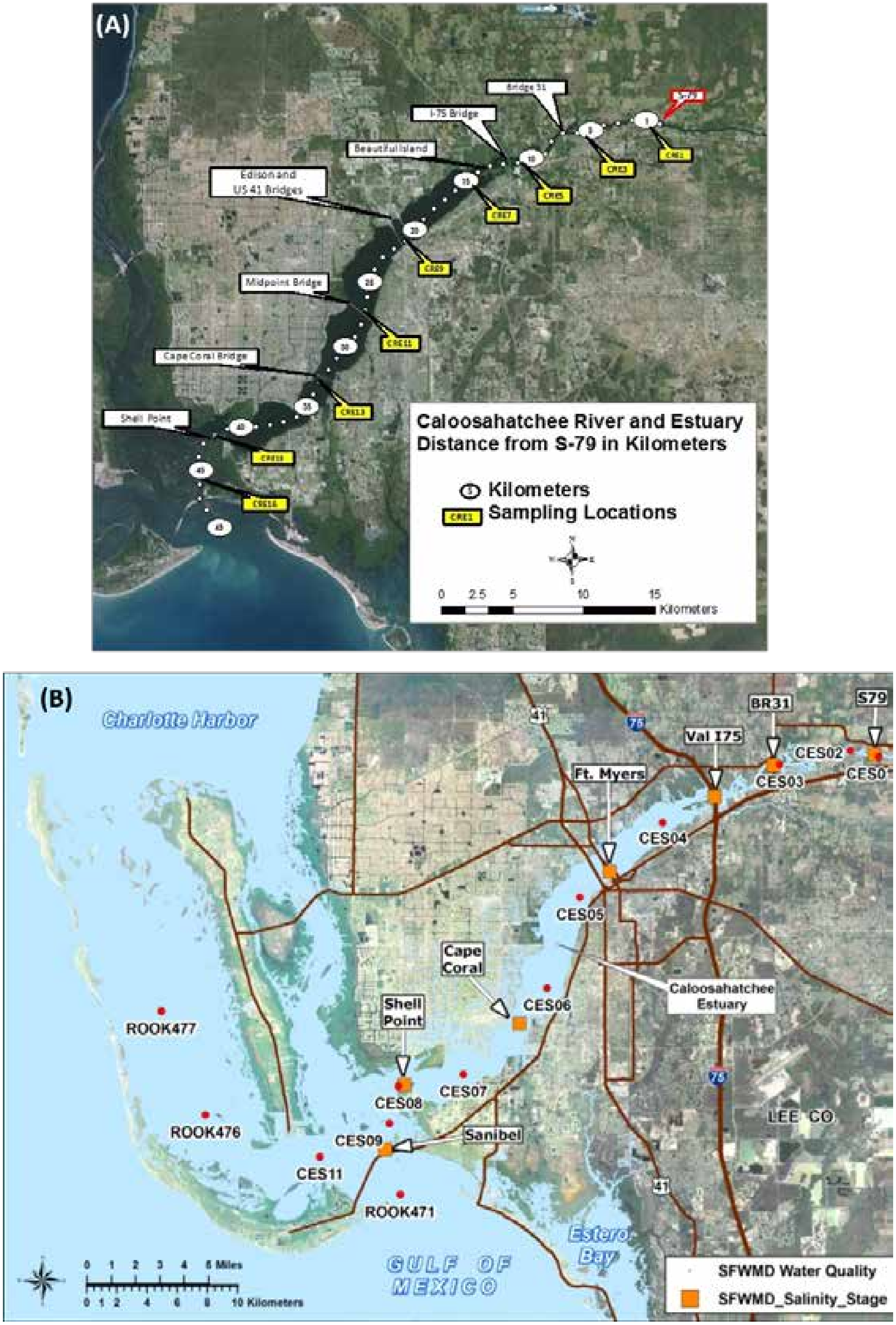


Figure A-16. (A) Map of the CRE from the APRS showing the major structures (S-79 and bridges), the distance downstream of S-79 (white circles), and the locations for the nine vertical profiling stations (yellow call-outs). (B) Site map for monitoring in the CRE.

The flow-through system offers a novel method of acquiring in situ surface water data while the research vessel is under way. The system consists of an intake ram attached to the stern, a flow meter, a Trimble global positioning system (GPS), an YSI 6600 multi-probe instrument, a bathymetric profiler, and a laptop computer with Streamline GEO software. The YSI 6600 was set up to record temperature, salinity, pH, turbidity, DO, and in situ CHL every 5 seconds. The intake ram was at 0.5 m below the water surface with an in-line pump to ensure continuous water flow through the system. Streamline Geo software permitted integration of the GPS and surface water data into an ArcGIS shape file useful both to display surface water properties in real time and for the post-processing of spatial data. Approximately 7–8 hours were required to travel from S-79 to San Carlos Bay at an average speed of 15.2 km per hour resulting in an average distance of 15–26 m between surface water recordings (Buzzelli et al. 2014a).

Patterns of surface water salinity and CHL with distance downstream from S-79 from three dates in 2012 (March 8, March 21, and April 12) were included in this study. Since the cruises occurred approximately every two weeks, the downstream location of the maximum CHL concentration (CHL_{max}) on each date was plotted versus freshwater inflow at S-79 averaged over the previous 14 days. All the cruise dates from 2012 and 2013 were included in a separate assessment of the longitudinal variation in isohalines and the CHL_{max}. Cruise data taken under higher discharges in 2014 (range: 0–2,030 cfs; mean: 761 ± 569 cfs) were omitted from this analysis.

On each of the cruises, the research vessel stopped at several mid-channel stations along the mid-estuary axis to conduct vertical profiling of temperature, salinity, pH, DO, turbidity, and CHL with the YSI 6600 multi-probe instrument. Recordings using the multi-probe instrument occurred at 1-meter intervals between the surface and bottom allowing for instrument stabilization between successive recordings. The vertical profiles for salinity, CHL, and DO were interpolated in two-dimensions (distance and depth) using a kriging technique to compare patterns among the three selected cruise dates.

Long-Term Monitoring of CHL

Water quality concentrations are monitored at approximately monthly intervals at multiple locations in the CRE (stations beginning with CES; **Figure A-16B**). These data are available from the DBHYDRO database (www.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu). CHL concentrations at CES03 in the upper CRE from April 1999 to April 2014 were included in this assessment. Since the relationships between freshwater inflow and estuarine indicators are often lagged in time and space, CHL was related to inflow averaged over different time periods. The monitoring dates were combined with a freshwater inflow series at S-79, which included the inflow on the sampling date (0 day) and inflow averaged 7 to 35 days prior. The relationship between CHL concentrations at CES03 was plotted over all time periods. The combined CHL-inflow data set was queried to determine freshwater inflows associated with the Impaired Waters Rule (Rule 62-303.353, F.A.C.) annual average CHL value of 11 µg L^{-1}. This exercise resulted in the determination of freshwater inflows linked to increased phytoplankton production in the upper CRE.

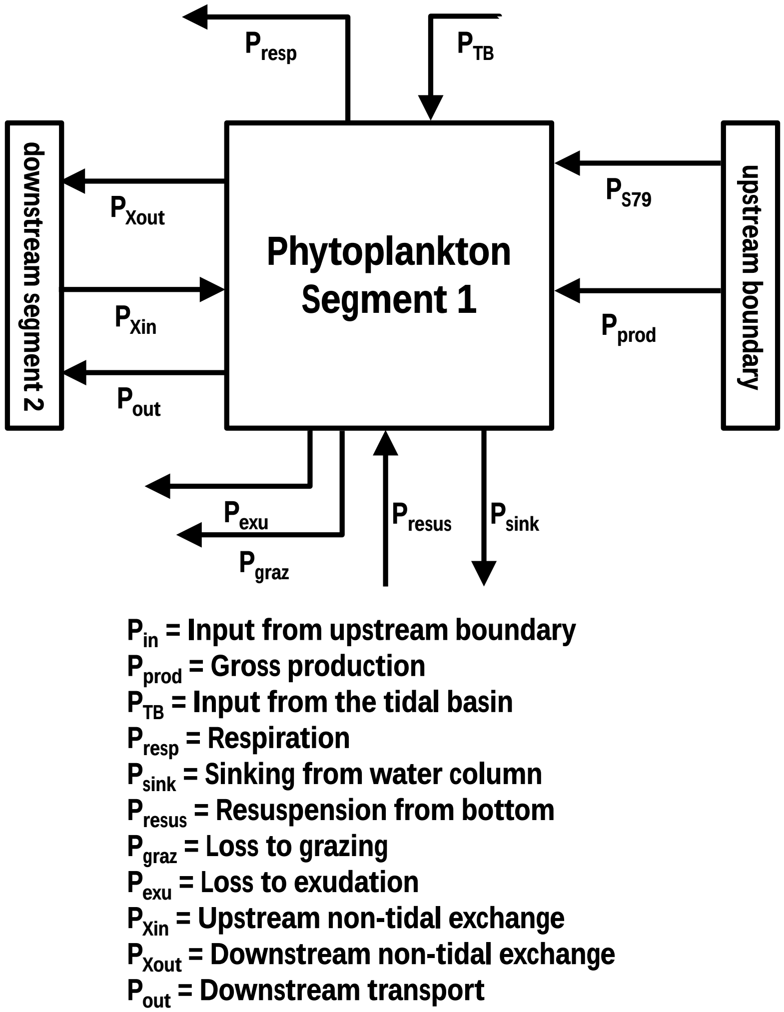
Segmented Simulation Model of the CRE

The CRE was split into three segments for development of a simulation modeling framework (Buzzelli et al. 2014b, 2014c). This model application focused on Segment 1 in the upper CRE (16.1 km from S-79; 1.5 x 10^7 square meters [m^2]; 2.1 x 10^7 m^3, see **Figure A-16** for river km). The model framework includes a box model for transport, external inputs, forcing functions that drive model processes, and biogeochemical process equations and coefficients (Buzzelli et al. 2014b). A fundamental assumption of estuary box modeling is that each box or segment is a fully mixed, homogeneous body of constant volume. The biogeochemical models use an integration interval of 0.03125 days (45 minutes) over simulations spanning 2,922 days from 2002 to 2009. The box model was driven by daily time series for freshwater inflow at the estuarine head and salinity for each segment and the downstream boundary. Physical transport of a water column constituent was the sum of advection, lateral inputs from tributaries and groundwater, and non-tidal dispersion. The time series for estuarine head from 2002 to 2009 (2,922 days) at S-79 was derived from DBHYDRO. The loadings of water column constituents at the upstream boundary were calculated as the product of the estuarine head and average monthly concentrations.

A watershed model was used to estimate the daily lateral input from tributaries and groundwater (Y. Wan, unpublished data). The loadings of water column constituents from the tributaries and groundwater were the product of the lateral inflows to each segment and the corresponding average monthly input concentration derived from Lee County, Florida, monitoring stations. Time series for the average daily salinity of each segment were generated using a predictive statistical model developed for the CRE (Qiu and Wan 2013).

Each of the three segments included a water column submodel to simulate the concentration of phytoplankton carbon, organic nitrogen and phosphorus, ammonium, nitrate-nitrite, ortho-phosphate, and sediment microalgae. Biogeochemical processes were modulated by variations in temperature, depth, and submarine light. The total attenuation coefficient for submarine light contained contributions from pure water, color, turbidity, and CHL. Attenuation due to color was estimated using a negative exponential relationship with average salinity of the segment (McPherson and Miller 1994, Bowers and Brett 2008, Buzzelli et al. 2012). Time series for the average turbidity of each segment were derived from monitoring data available through DBHYDRO. Phytoplankton was a key variable since it receives external inputs of CHL from the watershed, is the primary sink for inorganic nitrogen and phosphorus, is the primary source of autochthonous organic nitrogen and phosphorus, is important in submarine light extinction, and serves as an ecological indicator (Doering et al. 2006, Buzzelli 2011, Buzzelli et al. 2014b). The amount of phytoplankton biomass (e.g. CHL) is calculated every time step depending upon five source terms (input from S-79, input from the Tidal Basin, production, resuspension from the bottom, and dispersion) and six sink terms (downstream outflow, dispersion, respiration, sinking, exudation, and grazing; **Figure A-17**).

Dry season (November–April) results from the base model simulations (2002–2009) in Segment 1 were used in this study. Daily model predictions of CHL in the upper CRE were calibrated using monthly CHL concentrations averaged among the S-79, CES01, CES02, and CES03 locations (Buzzelli et al. 2014b). Similar to the field data, the model output was queried to determine freshwater inflows associated with the Impaired Waters Rule annual average CHL value of 11 µg L^{-1}. This exercise resulted in the determination of the desirable freshwater inflows below which there was the potential for phytoplankton blooms in the upper CRE.



$$dPhytodt^{-1} = [(P_{S79} + P_{TB} + P_{prod} + P_{resus} + P_{Xin}) -$$
$$(P_{out} + P_{Xout} + P_{resp} + P_{sink} + P_{exu} + P_{graz})]$$

Figure A-17. Schematic and definition of process terms that influence phytoplankton biomass (e.g. CHL) in the simulation model for the CRE.

Results

Adaptive Protocol Release Study

Freshwater inflow to the CRE through S-79 declined from January to March 2012 before reaching 0.0 cfs on March 27, 2012 (Buzzelli et al. 2014a). Two-week average inflow decreased from 627.8 to 556.3 cfs between March 8 and March 21 (**Table A-8**). There were a total of 1,559, 2,177, and 2,085 surface water recordings along the length of the CRE on March 8, March 21, and April 12, respectively (Buzzelli et al. 2014a). These highly resolved spatial data permitted visualization of the longitudinal patterns of salinity and CHL with changes in freshwater inflow (**Figure A-18**). The locations of the salinity of 10 isohaline moved upstream with reduced inflow;

it was located 14.6 km from S-79 on March 8 but only 0.7 km from S-79 on April 12 (**Table A-8**). Salinity ranged 5 to 6 from 0 to 14 km downstream before increasing from 6 to 35 over the remaining 26 km on March 8 (**Figure A-18A**). There were obvious variations in salinity along the length of the CRE on this date. On March 21, salinity ranged from 6 to 7 over the initial 10 km after which it increased linearly with distance downstream. Finally, salinity at S-79 was ~10 on April 12 after the cessation of inflow. It increased gradually down to ~14 km before exhibiting a smooth, linear increase over the remaining length of the estuary.

Table A-8. Results from the APRS on the CRE in the 2012 dry season. Included are the 14-day average inflow at S-79 (Q_{S79}), the location of the salinity of 10 isohaline from S-79 (S_{10}), and the location and value for the maximum concentration of chlorophyll *a* (CHL_{max}).

Date	Q_{S79} (cfs)	S_{10} (km)	CHL_{max} (km)	CHL_{max} (µg L^{-1})
3/8/12	627.8	14.6	12.9	11.1
3/21/12	556.3	11.1	12.8	10.2
4/12/12	0.0	0.7	2.6	25.6

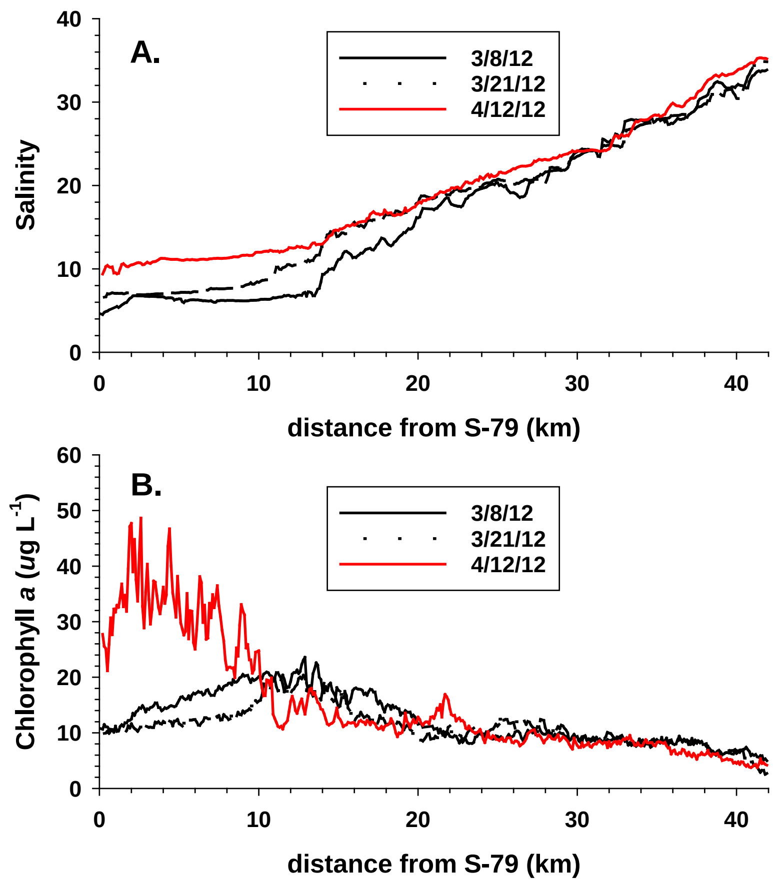


Figure A-18. Results of the APRS from March 8, 2012, March 21, 2012, and April 12, 2012: (A) surface water salinity versus distance downstream of S-79; and (B) surface water CHL versus distance downstream of S-79.

Similar to the salinity of 10 isohaline, the CHL_{max} migrated upstream with reduced discharge. While it was located at 12.8 km downstream of S-79 on March 21, it moved upstream to 2.6 km as inflow decreased leading up to the April 12 cruise (**Table A-8**). There was great variability in CHL (20–48 µg L^{-1}) from 0 to 10 km on April 12 compared to the previous two cruise dates (**Figure A-18B**). Thus, the location of the CHL_{max} in the upper estuary increased dramatically from 10.2 µg L^{-1} on March 21 to 25.6 µg L^{-1} on April 12 (**Table A-8**). CHL declined to 10–15 µg L^{-1} from 20 to 42 km downstream on all three cruise dates.

Interpolated contour plots derived from the vertical profiles validated upstream salinity and CHL encroachment as inflow decreased (**Figure A-19**). These profiles and plots illustrated depth-dependent patterns including a surface lens of fresh water that contributed to vertical salinity stratification on March 8 (**Figure A-19**, top left; Buzzelli et al. 2014a). It appeared that the vertical stratification evident in March gave way to horizontal gradients as saltier water moved upstream by April (**Figure A-19**, top center and top right). There appeared to be a topographic influence on hydrodynamic and biogeochemical processes due to the decrease in depth from 6 km (~7 m) to 15 km (~2.5 m) downstream of S-79.

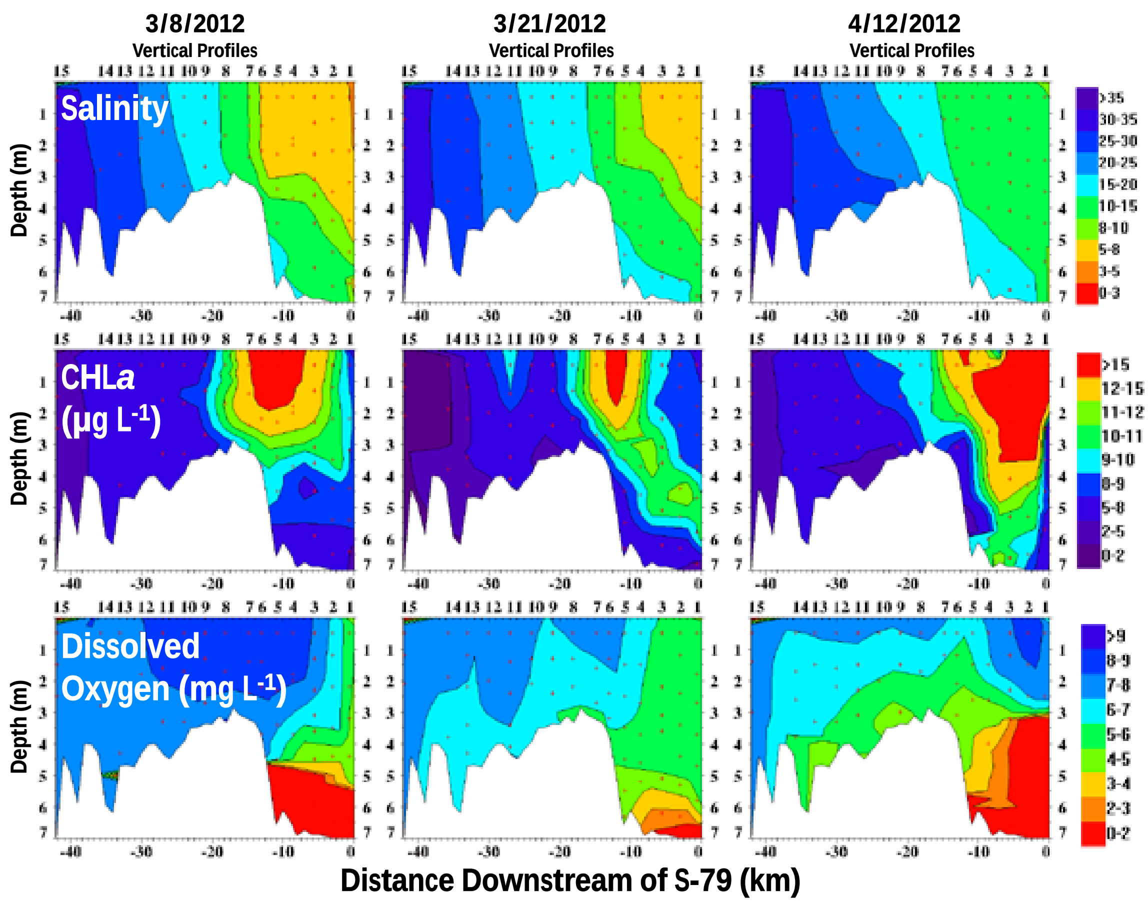


Figure A-19. Interpolated depth versus distance contour plots derived from vertical profiling from the APRS for three different cruise dates.
(Notes: APRS station designations from **Figure A-16A** are provided at the top of each plot. The horizontal axis is oriented from right to left to represent distance downstream of S-79. The vertical axis is depth. The top three plots show salinity ranging from 0 to 3 to > 35.0. The middle three plots show CHL ranging from 0 to 2 to > 15.0. The bottom three plots show DO concentrations ranging from 0 to 2 to > 9.0.)

The CHL_{max} was located ~13 to 20 km downstream under inflows of 500 to 1,000 cfs over all cruises in 2012 and 2013 (**Figure A-20**). Thus, the CHL_{max} extended vertically down a couple of meters as it was located in a shallower area of the estuary. This was evident on March 8 followed by a slight deepening of the surface layer CHL_{max} on March 21 (**Figure A-19**, middle left and middle center). The estuarine water parcel containing a greater amount of phytoplankton biomass located farther upstream on April 12 extended much deeper in the water column (~4.5 m; **Figure A-19**, right center). These attributes of depth, inflow, and primary production affect the potential for bottom water hypoxia in the upper CRE (**Figure A-19**, bottom row). Although there were bottom water DO concentrations £ 3 mg L^{-1} on March 8 and March 21, the vertical and horizontal extent of bottom water hypoxia was much greater on April 12.

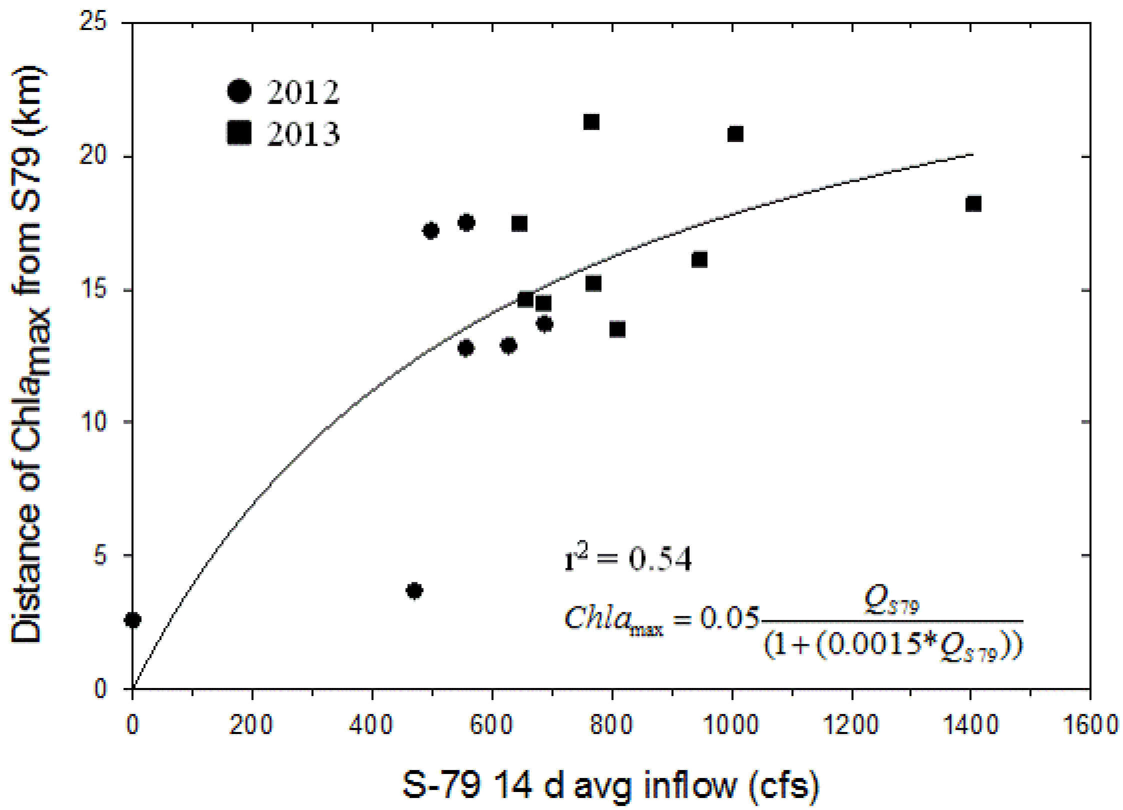


Figure A-20. Hyperbolic relationship between average (avg) freshwater inflow 14 days (d) before cruise date for the APRS and the location of the CHL_{max} in surface water of the CRE. (Notes: Results are from all cruises from dry seasons in 2012 and 2013. n = 1.)

Long-term Monitoring of Chlorophyll *a*

CHL at CES03 (7 km downstream of S-79) ranged from a minimum of 0.3 µg L^{-1} to maximum values of 73.0 and 98.8 µg L^{-1} in the dry and wet seasons, respectively (**Table A-9** and **Figure A-21**. CHL was low (< 10 µg L^{-1}) from 2002 to 2006 but appeared to be more variable from 2007 to 2011. The highest values were observed on April 28, 2009 (73.0 µg L^{-1}), and July 20, 2011 (98.8 µg L^{-1}). The seasonally averaged concentrations were highly variable in dry and wet seasons (8.6 ± 10.2 and 12.2 ± 15.0, respectively). The coefficient of variation was > 100% in both seasons. Averaging inflow over an increasing number of days preceding the field sampling at CES03 did not improve the correlation between the observed CHL concentrations and freshwater discharge (**Figure A-22**).

Table A-9. Descriptive statistics for CHL (µg L^{-1}) at station CES03 in the CRE from April 1999 to April 2014. The data set was split into dry (November–April) and wet (May–October) seasons. (Note: Included are the number of samples, range, median, average and standard deviation [Avg ± SD], and the coefficient of variation expressed as a percentage [CV = (SD/Avg)*100].)

Season	Number	Range	Median	Avg ± SD	CV (%)
Dry	93	0.3–73.0	5.5	8.6 ± 10.2	118
Wet	93	0.3–98.8	5.2	12.2 ± 15.0	123

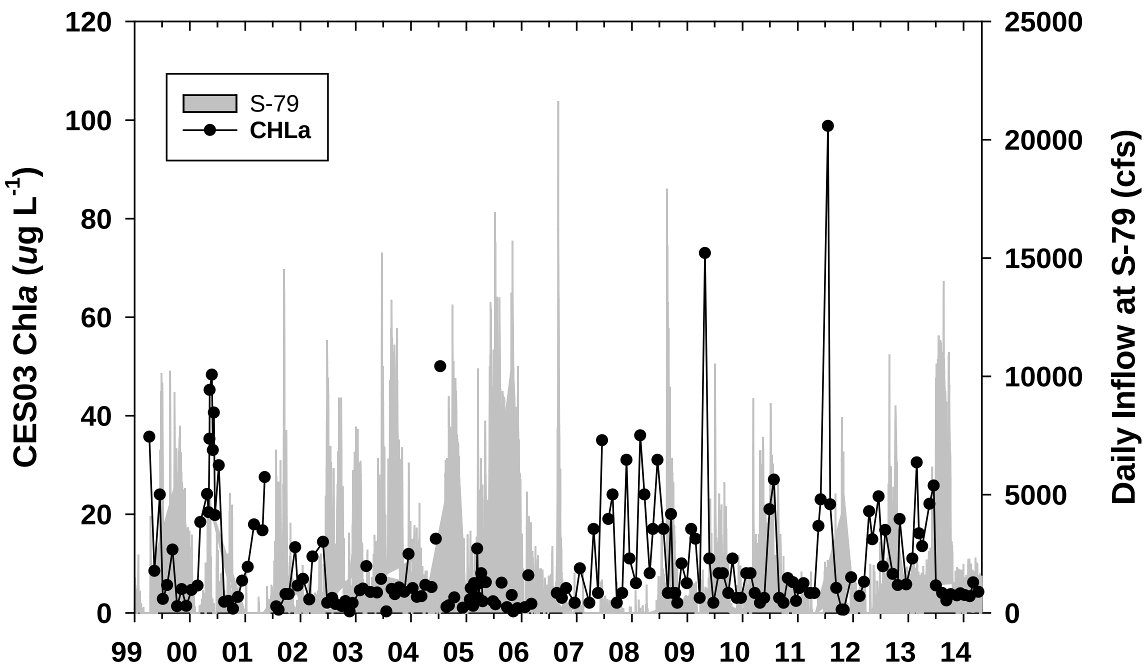


Figure A-21. Time series of water column CHL observed at station CES03 in the upper CRE. Average daily inflow at S-79 (right axis) is shown in grey.

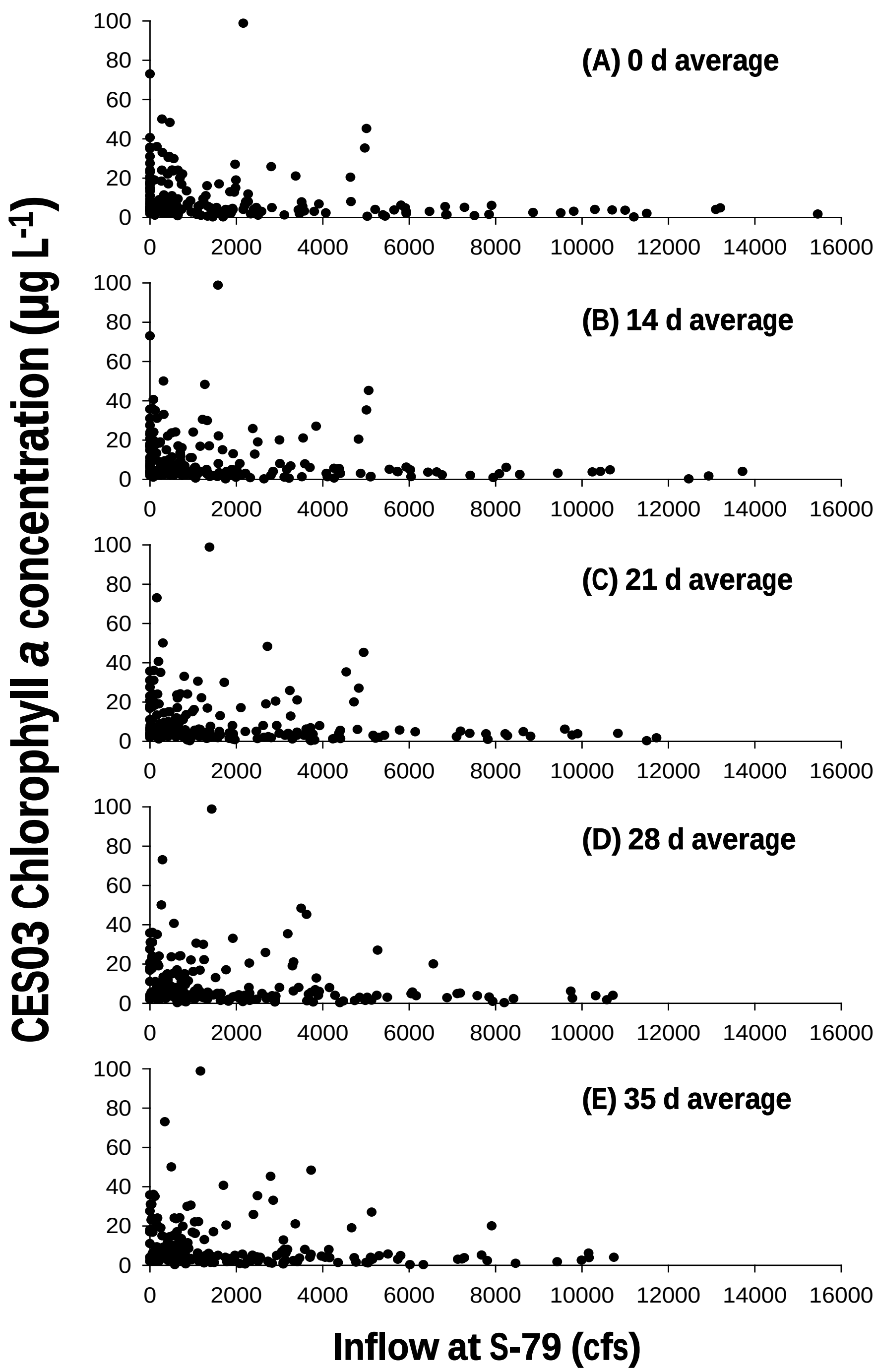


Figure A-22. Scatterplots of water column CHL observed at station CES03 in the upper CRE versus the average daily inflow at S-79: (A) inflow on CES03 sampling date; (B) inflow averaged over 14 days (d) prior to the sampling date; (C) inflow averaged over 21 days prior to sampling date; (D) inflow averaged over 21 days prior to sampling date; (E) inflow averaged over 35 days prior to sampling date.

Segmented Simulation Model of the CRE

Average daily CHL concentrations predicted for the upper CRE ranged from 0.6 to 31.3 µg L^{-1} from 2002 to 2009 (**Figure A-23**). The model was a reliable predictor as CHL approximated the average concentrations determined among multiple stations in the upper CRE (r = 0.61–0.76; **Table A-10**). Values were generally higher in the wet season (14.2 ± 4.0 µg L^{-1}) compared to the dry season (6.8 ± 2.3 µg L^{-1}; **Table A-10**). The simulation model predicted that average monthly CHL during the dry season in the upper CRE decreases exponentially with increased freshwater inflow (**Figure A-24**). However, there was a wide range of CHL concentrations that were possible when inflows were < 500 cfs.

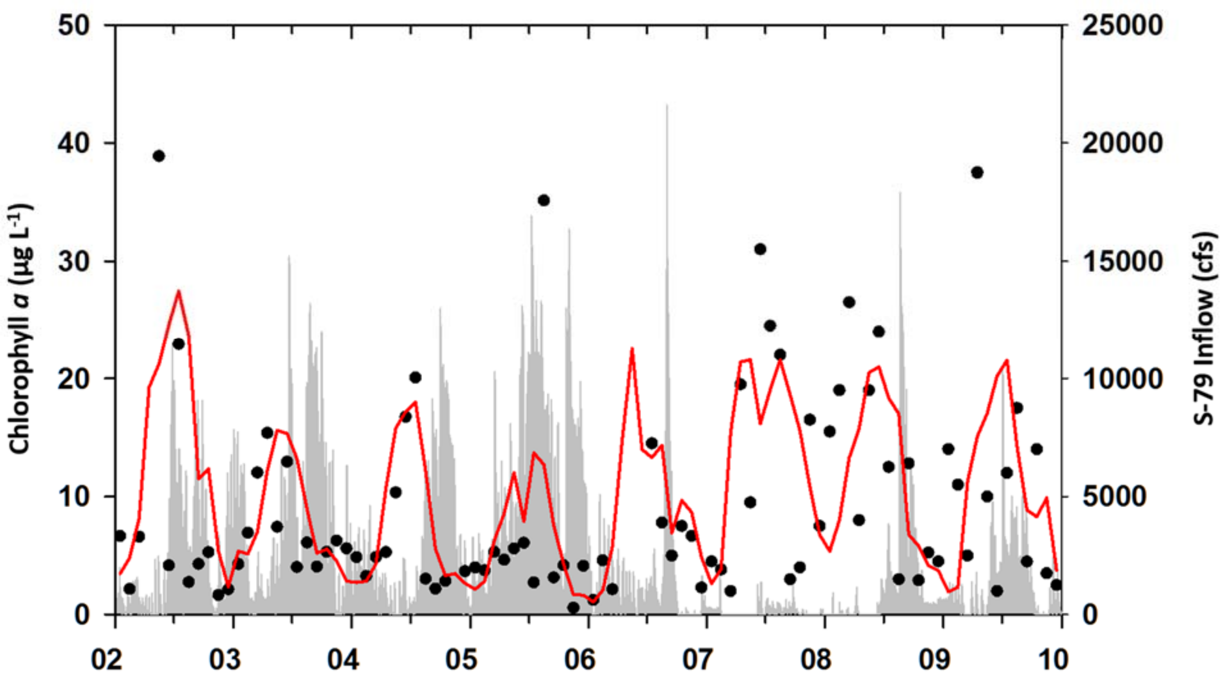


Figure A-23. Time series of water column CHL concentration predicted for the upper CRE (0–16 km downstream of S-79) using the simulation model.
(Notes: Data points represent the average CHL concentration averaged among four stations in the upper CRE (S-79, CES01, CES02, and CES03). Also shown are daily average flows from S-79.)

Table A-10. Model calibration results to simulation CHL concentration (µg L^{-1}) in the upper CRE (0–16 km from S-79) from 2002 to 2009.
(Notes: Included are the average + standard deviation for pooled monitoring data [CES01, CES02, CES03, and S-79] and the model. The correlation coefficient [r] between the data and the model was calculated using monthly average concentrations [n = 96 months].)

Season	Data	Model	r
Dry	7.4±4.5	6.8±2.3	0.61
Wet	9.4±3.9	14.2±4.0	0.76

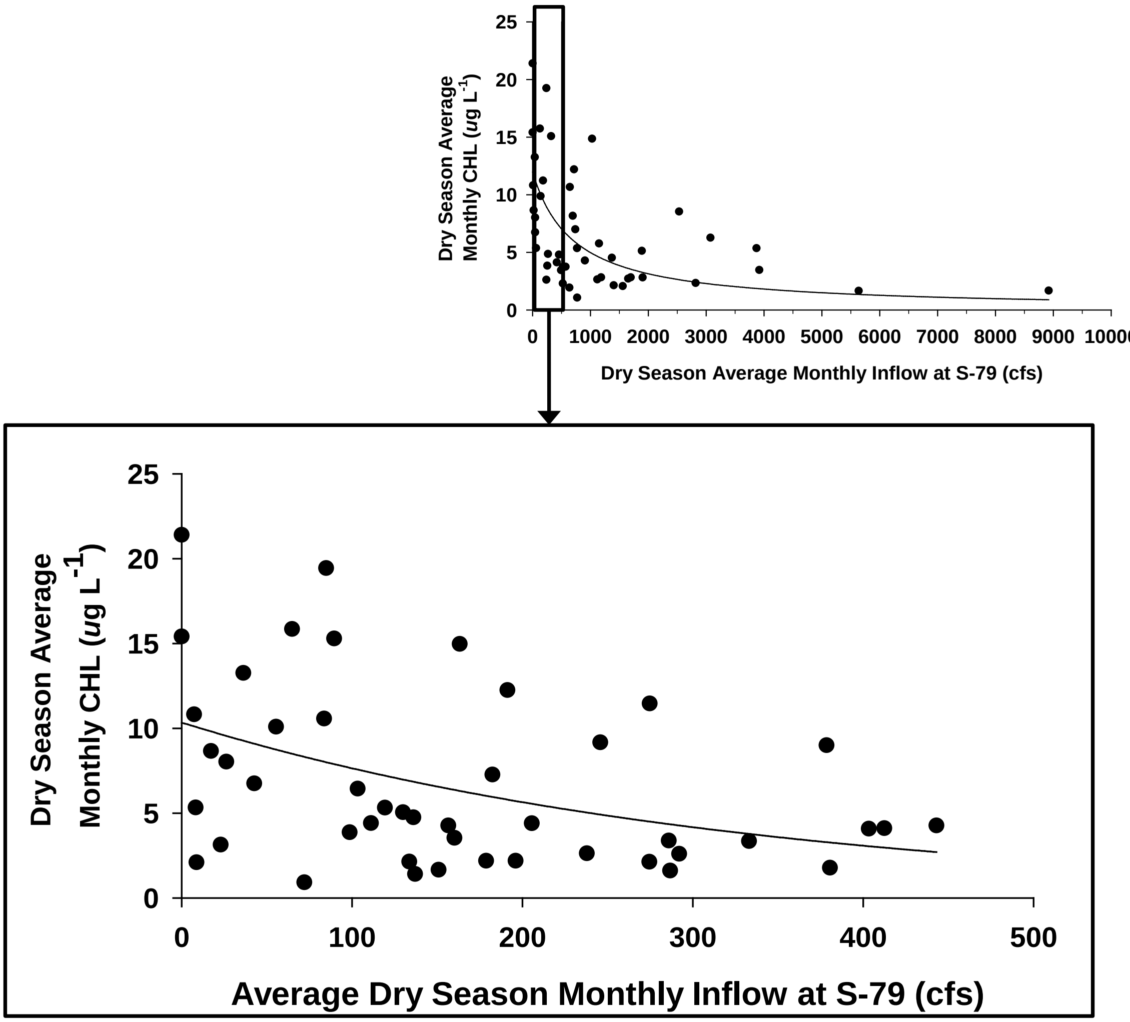


Figure A-24. Results from simulation model of the CRE. Average monthly inflow at S-79 (cfs) versus average monthly CHL concentration (µg L^{-1}) in upstream Segment 1. The zoomed scatterplot highlights inflows < 500 cfs.

An upper threshold of 11.0 µg L^{-1} was used as a critical criterion to query both the field and model CHL concentrations in the dry season (**Table A-11**). There were 24 measurements of CHL at CES03 that were > 11.0 µg L^{-1} (19.5% of all dry season measurements). Daily average inflows at S-79 ranged from 0 to 2,270 cfs averaging 469 ± 689 cfs over these measurements. For the model, there were 265 daily predictions of CHL in the upper CRE that were > 11.0 µg L^{-1} (18.3% of dry season simulation days). Inflow at S-79 ranged from 0 to 2,450 cfs averaging 269 ± 493 cfs for this subset of simulated days.

Table A-11. Summary of daily average inflows at S-79 when the CHL concentrations were > 11 µg L^{-1}. (Notes: Results from both field monitoring (top row) and the upper segment of the CRE simulation model [bottom row; Buzzelli et al. 2014b]. Water column CHL concentrations were determined at station CES03 from April 1999 to April 2014 [n = 259]. Using the model, water column CHL concentrations were predicted for the upper CRE [0 to 16 km from S-79] every day from 2002 to 2009 [n = 2,120 days]. Values include the averages and standard deviations [Avg ± SD] for CHL and the freshwater inflows from S-79 [Q_{S79}; cfs]. Results are for dry season days only [November–April] for both the field [n = 123] and model [n = 1,450].)

Source	Count	CHL > 11 µg L^{-1} Avg ± SD	Q_{S79} (cfs) Avg ± SD
Data	24 (19.5%)	31.8 ± 51.4	469 ± 689
Model	265 (18.3%)	16.1 ± 3.8	269 ± 493

Discussion

Reduced freshwater inflow has clear biogeochemical implications for shallow, microtidal estuaries around the Gulf of Mexico (Murrell et al. 2007, Tolley et al. 2010). Internal cycling of materials becomes more important with reduced inflow; overall biological productivity can be severely inhibited as freshwater input declines (Livingston 2007). These attributes can favor phytoplankton production in excess of transport and grazing and the deposition of phyto-detritus in upstream sediments (Radabaugh and Peebles 2012, Cloern et al. 2014). Decreased vertical mixing coupled with enhanced deposition of organic matter can fuel hypoxia in the bottom water under reduced freshwater inflow (Doering et al. 2006, Murrell et al. 2007, Tolley et al. 2010).

Combined results suggested that daily inflows < 500 cfs would result in the CHL_{max} located less than ~13 km downstream of S-79. This sequence would position the CHL_{max} above the deeper channel (~7 m) where bottom water DO concentrations £ 3 mg L^{-1} occur. Thus, diminished freshwater inflow could enhance both salinity stratification and the deposition of phyto-detritus (Murrell et al. 2007, Radabaugh and Peebles 2012). The possibility for hypoxia in the upper CRE is heightened given that both sediment organic content and rates of sediment oxygen demand are greater in the upper CRE (Buzzelli et al. 2013a). Finally, at the estuary scale there is increased heterotrophy (e.g. the respiration of organic matter) with reduced freshwater inflow (Buzzelli et al. 2013d).

Previous studies of the CRE have established (1) high CHL in surface waters is correlated with low DO in bottom waters, (2) hypoxia occurs most often in the upper estuary, and (3) both the magnitude and position of the CHL_{max} depend on freshwater inflow (Doering et al 2006, Wan et al 2013, Buzzelli et al. 2014a). Research into fine-scale responses of water quality to variable freshwater inflow (APRS) has provided some additional insight. While the APRS provides highly resolved spatial and temporal data, there have been limited surveys at very low inflows. More cruises need to be conducted at inflows of 0 to 500 cfs to better quantify the discharge required to mitigate the potential for hypoxia in the upper CRE. These efforts will improve the predictions of CHL_{max} and permit quantification of freshwater inflows required to avoid hypoxia in the upper CRE.

The model (< 269 cfs) and field (469 cfs) results indicated that freshwater inflows of < 500 cfs were associated with CHL concentrations greater than the Impaired Waters Rule standard of 11.0 µg L^{-1}, annual average. Both the empirical and simulation estimates of the inflow magnitudes are valuable results of this study. Monthly monitoring of CHL concentrations at specific locations provides an indicator of water quality, but does not account for dynamic changes in phytoplankton assemblages on scales of hours-weeks. Whereas CHL is regularly monitored as a proxy for biomass, phytoplankton production is modulated by non-linear interactions among several environmental drivers (Cloern et al. 2014). Additionally, many of these biogeochemical interactions are lagged in time and space.

In terms of water quality modeling, the many process-based parameters introduce uncertainty to the predictions. Confidence in model predictions is largely dependent upon the quality of both the experimental and calibration data (Buzzelli et al. 2014a).

While this modeling effort has great utility to evaluate estuarine responses over a range of inflow and nutrient loading conditions, it was highly aggregated spatially (Buzzelli et al. 2014a, 2014b). The development and implementation of a hydrodynamic-water quality modeling framework with greater spatial resolution could greatly benefit quantification of the inflows required to support optimal levels of phytoplankton and other water column indicators (Wan et al. 2012, Condie et al. 2012, Funahashi et al. 2013, Azevedo et al. 2014).

Component Study 4: Zooplankton Response to Freshwater Inflow in the CRE

Peter Doering

Abstract

Freshwater inflow to some estuaries, including the CRE, is regulated through control structures. Zooplankton assemblages provide an essential food web link whose position in the estuary fluctuates with inflow. Unfortunately, zooplankton habitat can be both impinged and compressed due to the presence of a water control structure as inflow is reduced in the dry season. This study assessed impingement and habitat compression for zooplankton under reduced inflow. Data used were from a CRE study conducted by Florida Gulf Coast University from 2008 to 2010. Zooplankton samples were collected monthly at each sampling site at night during a flood tide. The centers of abundance (COA) for the 13 taxa investigated migrated downstream and upstream as freshwater inflow increased and decreased, respectively. Both habitat compression and impingement were potentially harmful for zooplankton assemblages in the estuary. Impingement was possible if inflow from the S-79 structure ranged from 98 to 566 cfs and averaged 412 ± 165 cfs. Almost all taxa investigated (except *Menidia*) experienced habitat compression if the COA was < 12 km downstream of S-79.

Introduction

Like many drowned river-valley type estuaries, the CRE is funnel shaped, being narrow near its head waters and wide at its mouth. Typically, this geomorphology results in a longitudinal volumetric gradient increasing from the head to the mouth of the estuary. The COA for planktonic organisms have been shown to move upstream and downstream as freshwater inflow decreases and increases, respectively (Peebles et al. 2007). This response to inflow coupled with the geomorphology of the estuary means that the volume of open water habitat available to planktonic populations varies with freshwater inflow (Peebles and Greenwood 2009). If the longitudinal dispersion of the population remains constant, the volume of water available for occupancy decreases with diminished inflow and the upstream movement of the organisms. The crowding of organisms into a relatively confined space (habitat compression; Crowder 1986, Copp 1992, Eby and Crowder 2002) may result in increased predation and competition for limited food resources. Some organisms may be forced to utilize habitat that is physiologically suboptimal and this may result in lower growth and survival (Petersen 2003). Many estuaries, including the CRE, have water control structures (e.g. dams) that regulate freshwater inflow (Franklin Lock and Dam or S-79). These structures block upstream movement of planktonic organisms with reduced inflow and serve as barriers to adult fish migration (impingement; Peebles and Greenwood 2009). Impingement against a water control structure such as S-79 in the upper CRE can exacerbate habitat compression.

The objectives of this study were to demonstrate the compression of the zooplankton community with upstream translation in the CRE, demonstrate the occurrence of impingement of zooplankton against S-79, and determine the discharges at S-79 that promote habitat compression and impingement.

The source of data for the analysis was a 24-month study of plankton in the CRE conducted by Florida Gulf Coast University (May 2008–April 2010; Tolley et al. 2010). The overall goal of the project was to establish linkages between variability in freshwater inflow and ecosystem condition by characterizing and quantifying the responses of estuarine phytoplankton, zooplankton, and benthic microalgae. Major details of the study design and sampling routine, extracted from Tolley et al. (2010), are given below. The present analyses were conducted by SFWMD staff.

Methods

Florida Gulf Coast University Plankton Surveys 2008–2010

This study used distance upstream from the estuary mouth to reference stations and patterns. A total of seven zones were sampled from Point Ybel, Sanibel, in San Carlos Bay to S-79. There were two stations (downstream and upstream) within each zone for a total of 14 stations per sampling (**Figure A-25** and **Table A-12**). The use of zones was not based on the identification of strata along the estuarine gradient but simply facilitated station location and sampling along the ~47-km transect. Zooplankton sampling sites were fixed for all collections. The position of the collection vessel was recorded at the beginning of each zooplankton tow using GPS. Mean distance between adjacent sampling sites was 3.26 ± 2.01 km. The system was sampled monthly for 24 months (May 2008–April 2010).

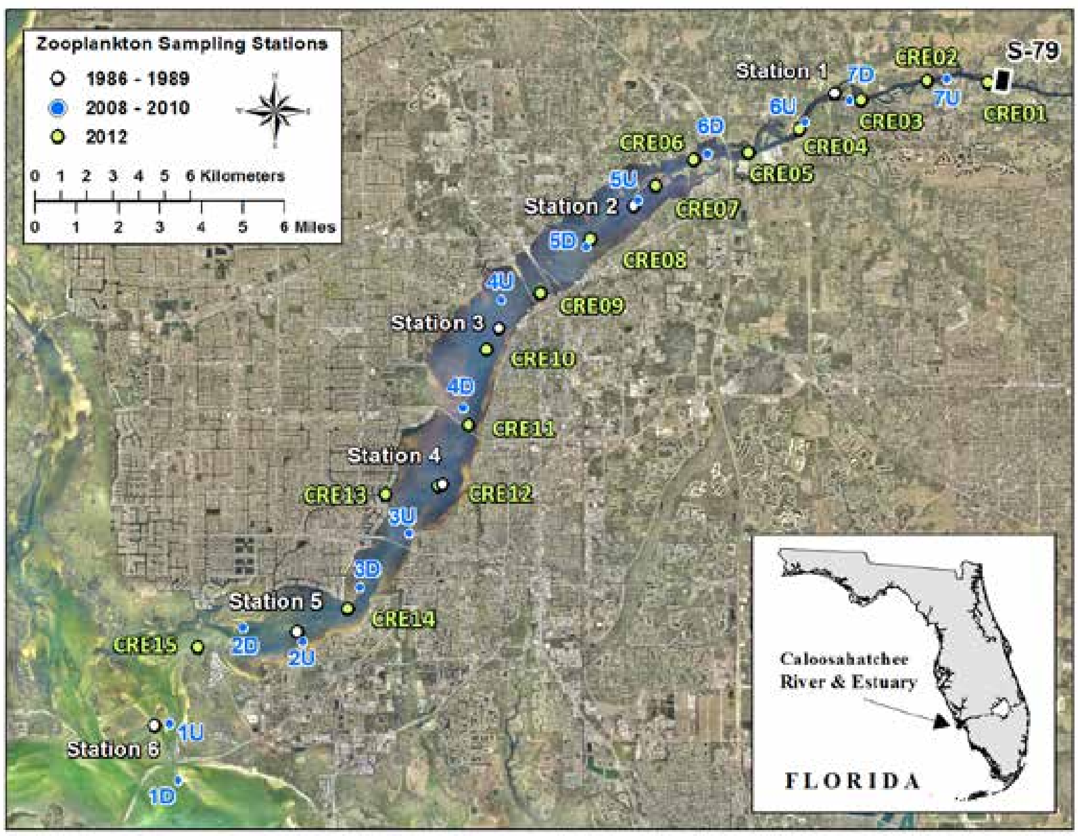


Figure A-25. Zooplankton sampling stations within the CRE. The Franklin Lock and Dam (S-79) are located at ~43.5 km upstream of Shell Point. Data collected from 2008 to 2010 were used in this study.

Table A-12. Sampling stations for biological and water quality data (May 2008–April 2010). (Notes: Depth represents the mean maximum water depth recorded at each station during biological sampling. D – downstream and U – upstream stations within each zone, with zones as described in the text.)

Zone	Station	River (km)	Latitude	Longitude	Depth
1	D	-5.9	26.4776	82.01157	2.92
	U	-3.6	26.49721	82.01514	3.09
2	D	2.5	26.53089	81.98688	3.96
	U	5.2	26.52616	81.96375	2.91
3	D	7.6	26.54528	81.94169	4.06
	U	10.6	26.56413	81.92283	3.88
4	D	16.2	26.60805	81.9022	3.73
	U	20	26.64585	81.88743	2.53
5	D	24.2	26.66452	81.85461	1.97
	U	26.9	26.68076	81.83474	2.03
6	D	30.2	26.69704	81.808	2.97
	U	34.4	26.70864	81.77011	4.38
7	D	37.1	26.71587	81.75259	3.83
	U	41.0	26.72397	81.71516	1.64

Zooplankton samples were collected monthly at each sampling site at night during a flood tide. Standard zooplankton collection gear consisted of a 500-micrometer Nitex mesh, 0.5-m mouth diameter, conical (3:1 aspect ratio) plankton net, equipped with a three-point bridle, 1-liter cod-end jar, 20 kilograms of weight suspended from the mouth ring, and a General Oceanics model 2030R flowmeter suspended at the center of the net's mouth. Deployment at each site consisted of a three-step oblique tow that divided fishing time equally between bottom, mid-depth, and surface waters. Tow duration was 5 minutes with tow speed estimated at 1.0–1.5 meters per second. Net position in the water column was regulated using a gunwale-mounted winch with metered tow line. Flowmeter readings were recorded before and after deployment to calculate the volume of water filtered during each tow.

Data Analysis

Longitudinal variations in the volume of the CRE were determined using interpolated bathymetry data and hypsometric assessment of distance downstream versus cumulative volume (similar to Buzzelli et al. 2013a). Bathymetry data are available by request from SFWMD. The volume of water contained in each 1-km segment of the estuary from S-79 to Shell Point was calculated.

Organisms captured were identified to the lowest practical taxon. Quality control and assurance procedures are described in Tolley et al. (2010). For each sampling event, the density-weighted COA (rkm_U) within the sampling space was calculated following Peebles et al. (2007) and Peebles and Greenwood (2009). The density weighted COA was calculated using **Equation A-8**:

$$rkm_U = \sum (\text{km} \cdot \text{U}) / \sum \text{U} \qquad \textbf{\textit{A}.8}$$

where U is the organism density (number per cubic meter [#/m^3]) at a station and *rkm* is the distance (km) of the station from Shell Point. $\sum$ U is the sum of organism density across all stations for each sampling date. For each sampling date, the quantity (km · U) is calculated for each station. These are summed and divided by $\sum$ U. rkm_U was correlated with freshwater discharge (Q) at S-79 averaged over the 1 to 120 days prior to sampling. A linear regression of rkm_U on transformed freshwater inflow (ln(Q+1)) was computed for the “lagged inflow” with the highest correlation coefficient (Tolley et al 2010). Inflows were calculated for lags of 60 days or less as these were considered most likely to be achievable through management of inflows at S-79. Inflows were averaged over 0, 3, 7, 14, 18, 20, 21, 30, 45, and 60 days prior to sampling.

Taxa used for the evaluation of impingement and habitat compression were selected from Tolley et al (2010). Tolley et al (2010) calculated regressions relating the location of the COA to natural log transformed freshwater inflow at S-79 for over 60 taxa (see Table 3.7.1.1 in Tolley et al. 2010). The 11 marine species with intercepts occurring furthest upstream (COA when inflow was 0 cfs) were evaluated for impingement and habitat compression (**Table A-13**). Based on the regression equations (see Table 3.7.1.1 in Tolley et al. 2010), the calculated positions of these 11 species when inflow was 0.0 cfs was 67.3 km upstream of Shell Point or 24 km upstream of S-79. These responses made them good candidates to experience habitat compression and impingement. Because of their high relative abundance and importance in the food web (Tolley et al. 2010), adult (*Anchoa mitchilli*) and juvenile (*Anchoa spp*.) anchovies were also included in the analysis.

Table A-13. List of organisms evaluated for potential habitat compression and impingement on S-79.

Taxon	Type
Clytia spp.	jellyfish
Lironeca spp.	isopod
Edotia triloba	isopod
Bowmaniella brasilliensis	mysid
Americamysis almyra adults	mysid
Americamysis spp. juveniles	mysid
Psuedodiaptomus pelgicus	copepod
Gobiosoma spp. postflexion larvae	fish
Menidia spp. preflexion larvae	fish
Gobiidae preflexion larvae	fish
Microgobius spp. postflexion larvae	fish
Anchoa mitchilli adult	fish
Anchoa mitchilli juveniles	fish

Potential habitat compression and impingement on S-79 were investigated using the spatial abundance quantile approach outlined by Peebles and Greenwood (2009). This approach utilizes the locations of the 10^{th} and 90^{th} deciles of cumulative abundance to assess impingement and habitat compression. Abundance, represented as organism density (#/m^3), was summed for each monthly survey to produce a total monthly value. Monthly density at individual stations was then summed sequentially in the upstream direction, and the resulting sums were expressed as a percentage of total monthly density. This process is analogous to creating a cumulative distribution curve or function, except that it sums sequential density values from successive stations along a transect instead of summing data-class frequencies. The location (rkm) of the 10^{th} (the lower decile) and 90^{th} percentiles (the upper decile) of total monthly density were interpolated linearly.

These linear interpolations were always made between the station with the highest percentile < 10 or < 90 and the next station upstream. The inter-decile range (IDR) is the distance in river km between the locations of the 10th and 90th abundance deciles. Monthly surveys were excluded from this analysis if > 10% of the catch was encountered at the downstream-most station, or if there were fewer than three stations with non-zero densities (Peebles and Greenwood 2009).

We tested the hypothesis that habitat volume decreases as the COA translates upstream (habitat compression). For each taxon investigated, the relationship between rkm_U and the two deciles was modeled using linear least squares regression (Peebles and Greenwood 2009). The positions of the 10th and 90th deciles were calculated for a series of rkm_U ranging from river km 15 to river km 40. In addition, the IDR was also calculated. For each rkm_U, the volume of water available for occupation (habitat volume) was calculated by combining estimates of estuarine segment volumes with the IDR. The segments containing the location of the upper and lower deciles were determined and the volumes of these and intervening segments summed to estimate the volume of water available for occupation. For each taxon investigated, this procedure yielded a series of rkm_U and potential habitat volumes occupied by 80% of the cumulative catch. This approach was used to determine if habitat volume decreases as rkm_U translates upstream or whether this decrease was offset by increased dispersion as measured by the IDR (Peebles and Greenwood 2009).

Impingement was assessed by examining the location of the upper abundance percentile (90th percentile) as a function of lagged freshwater inflow at S-79. Inflows were calculated for lags of 60 days or less as these were considered most likely to be achievable through management of inflows at S-79. Inflows were averaged over 0, 3, 7, 14, 18, 20, 21, 30, 45, and 60 days prior to sampling. For organisms whose location in the estuary moves upstream as freshwater inflow declines, impingement was indicated if a threshold inflow was reached at which the position of the 90th abundance decile ceases to change upon further reduction in inflow. Conversely, as inflows increased above this threshold, impingement was relieved and the position of the 90th abundance decile moved downstream. This threshold inflow was determined by a change point analysis using the SAS NLIN procedure as described by Schwarz (2013). A conditional regression approach is employed (**Figure A-26**):

$$\text{If } Y < CP \text{ then } Y = b; \text{ otherwise } Y = b + m\,(X - CP) \qquad \textbf{\textit{A}.9}$$

where Y is the location of the 90th decile in the estuary, X is lagged inflow, CP is change point or threshold inflow, b is the constant or river km where position of the 90th decile becomes independent of inflow, and m is slope or the rate at which the position of the 90th decile changes as inflows increase above the threshold.

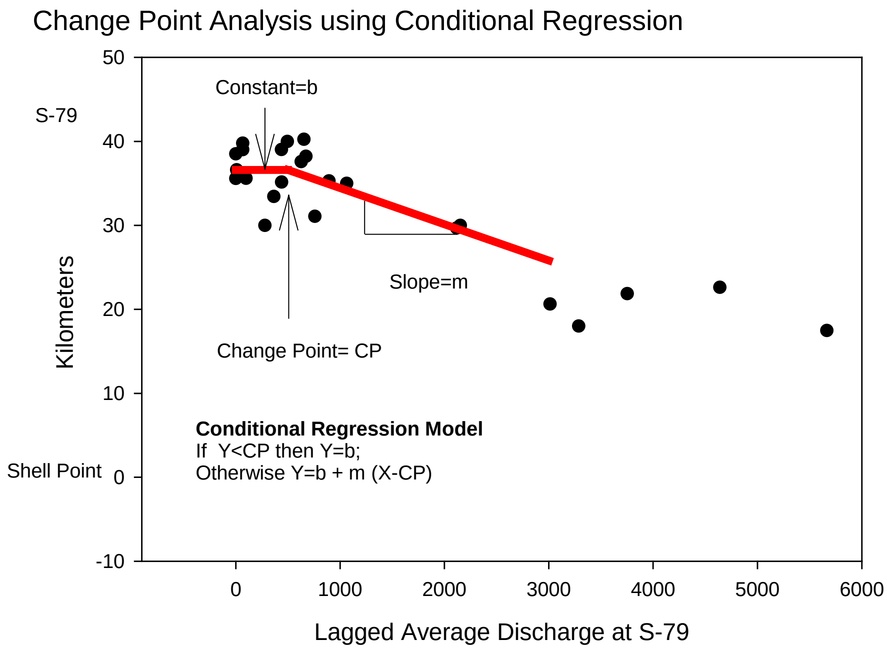


Figure A-26. Change point analysis using conditional regression. (Notes: The y-axis is the position of the 90th abundance decile in the CRE. The x-axis is discharge averaged over a number of days before sampling, which ranged between 0 and 60.)

Results and Discussion

Volume of 1-km increments ranged from 5.0 x 10^5 m^3 to 1.3 x 10^7 m^3 along the longitudinal gradient of the CRE (**Figure A-27**). Volume was greatest ~2 to 3 km and 14 to 16 km upstream of Shell Point. There is a major constriction and reduction in the volume of individual segments upstream of about km 30 (Beautiful Island).

The COA's for the 13 taxa investigated migrated downstream and upstream as freshwater inflow increased and decreased, respectively (**Table A-14**). This response was revealed by the negative slope in regression relationships. Freshwater inflow at S-79 explained from 15 to 50% of the variability in location of the COA's of the various taxa. Most taxa responded to inflows averaged over 45 or 60 days. This agrees with a previous analysis of the data by Tolley et al. (2010) that found most taxa responding to inflows averaged over ~50 days. For twelve of the thirteen taxa, COA's were sometimes located upstream of river km 30, in the narrow region of the estuary where habitat volume is greatly reduced, indicating the potential for both habitat compression and impingement (**Figure A-28**). Inflows at S-79, required to locate the COA of each taxon at river km 30, ranged from 6.6 to 1,362 cfs, and averaged (± standard deviation) 259 ± 378 cfs among the 13 taxa. The median was 128 cfs with 25th and 75th percentiles of 29.7 and 289 cfs, respectively.

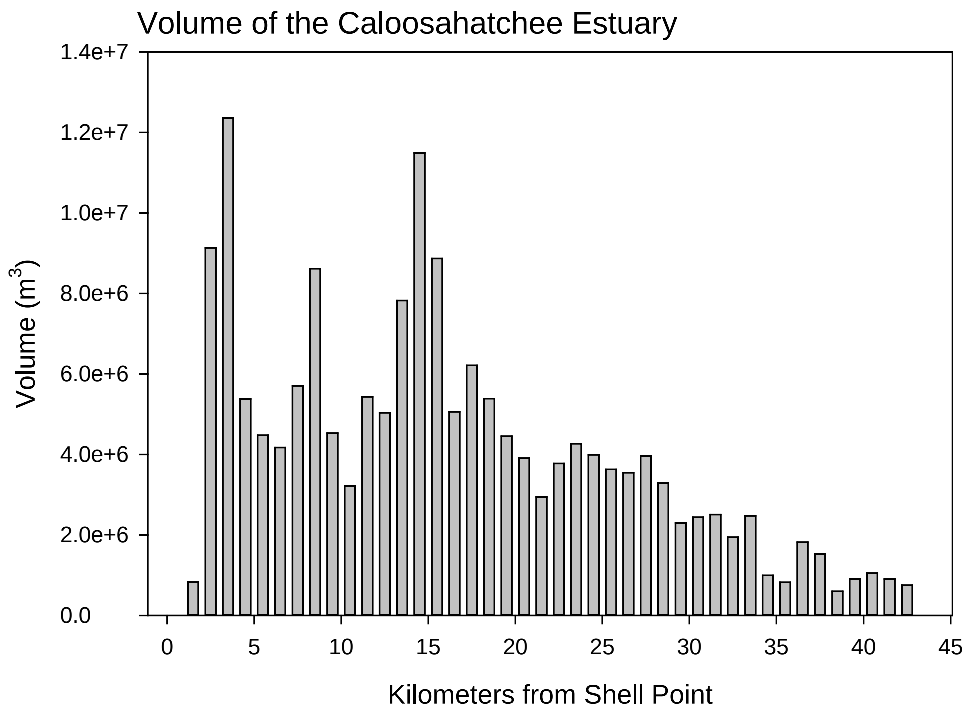


Figure A-27. Volume of the CRE in 1-km increments, Shell Point (0 km) to the S-79 (43 km).

Table A-14. Regression relationships between freshwater inflow at S-79 (x) and the location of the COA (rkm_U; y) in the sampling space.
(Notes: n is the number of observations, a is the intercept, b is the slope, p is the level of statistical significance, and r^2 is the coefficient of determination. Days are the number of days prior to each sampling date that inflow [Q] was averaged. In general, regression equations were of the form rkm_U = a – b (ln(Q+1)) except where noted. Also given is the inflow required to locate the COA at 30 km upstream of Shell Point where volume of the estuary begins to increase.)

Taxon	n	a	b	p	r^2	Days	30 km (cfs)
Lironeca spp.	24	36.73	-3.31	0.001	0.43	14	6.6
Edotia triloba	24	47.31	-3.89	0.001	0.41	45	85.0
Bowmaniensis brasilliensis	24	44.76	-4.31	0.002	0.36	45	29.7
Americamysis almyra adults	24	49.90	-3.51	0.002	0.35	45	288.9
Americamysis spp. juveniles	24	46.72	-3.44	0.004	0.32	45	128.1
Psuedodiapotomus pelagicus	22	44.10	-5.37	0.001	0.46	60	12.8
Gobiosoma spp. postflexion larvae	20	51.85	-5.91	0.008	0.33	60	39.4
Microgobius spp. postflexion larvae	17	71.82	-7.88	0.001	0.54	60	200.8
Gobiidae preflexion larvae	24	45.72	-5.21	0.001	0.36	60	19.5
Menidia spp. preflexion larvae	17	76.31	-7.36	0.005	0.38	60	540.8
Anchoa mitchilli adults [a]	24	3.50	0.00	0.002	0.34	14	518.4
Anchoa spp. juveniles [b]	24	31.88	0.00	0.065	0.15	3	1,362.3

a. ln(rkm_U) = a - b(Q)
b. rkm_U =a - b(Q)

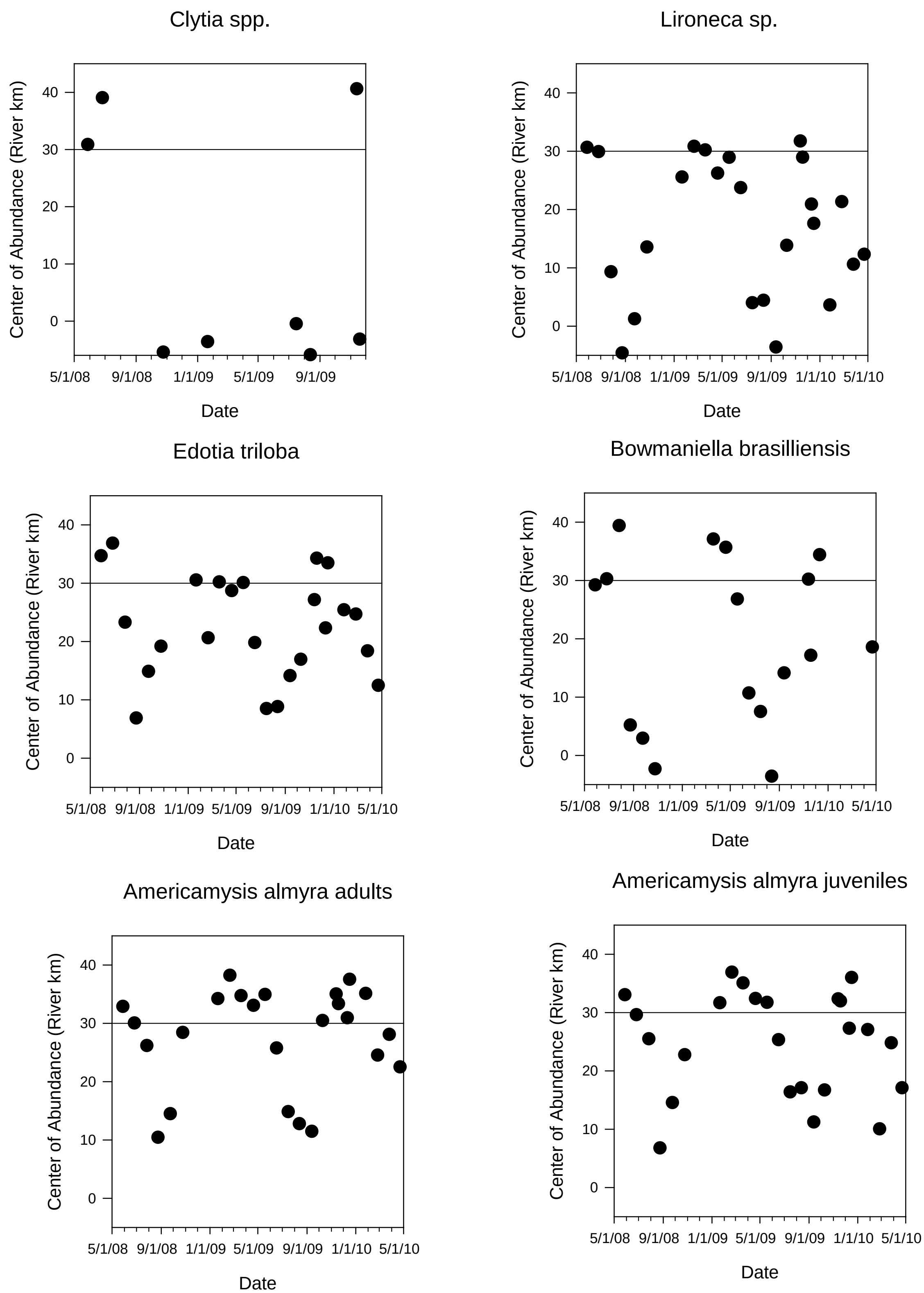


Figure A-28. COA for various taxa during the study period. Upstream of the reference line at 30 km, habitat volume is reduced.

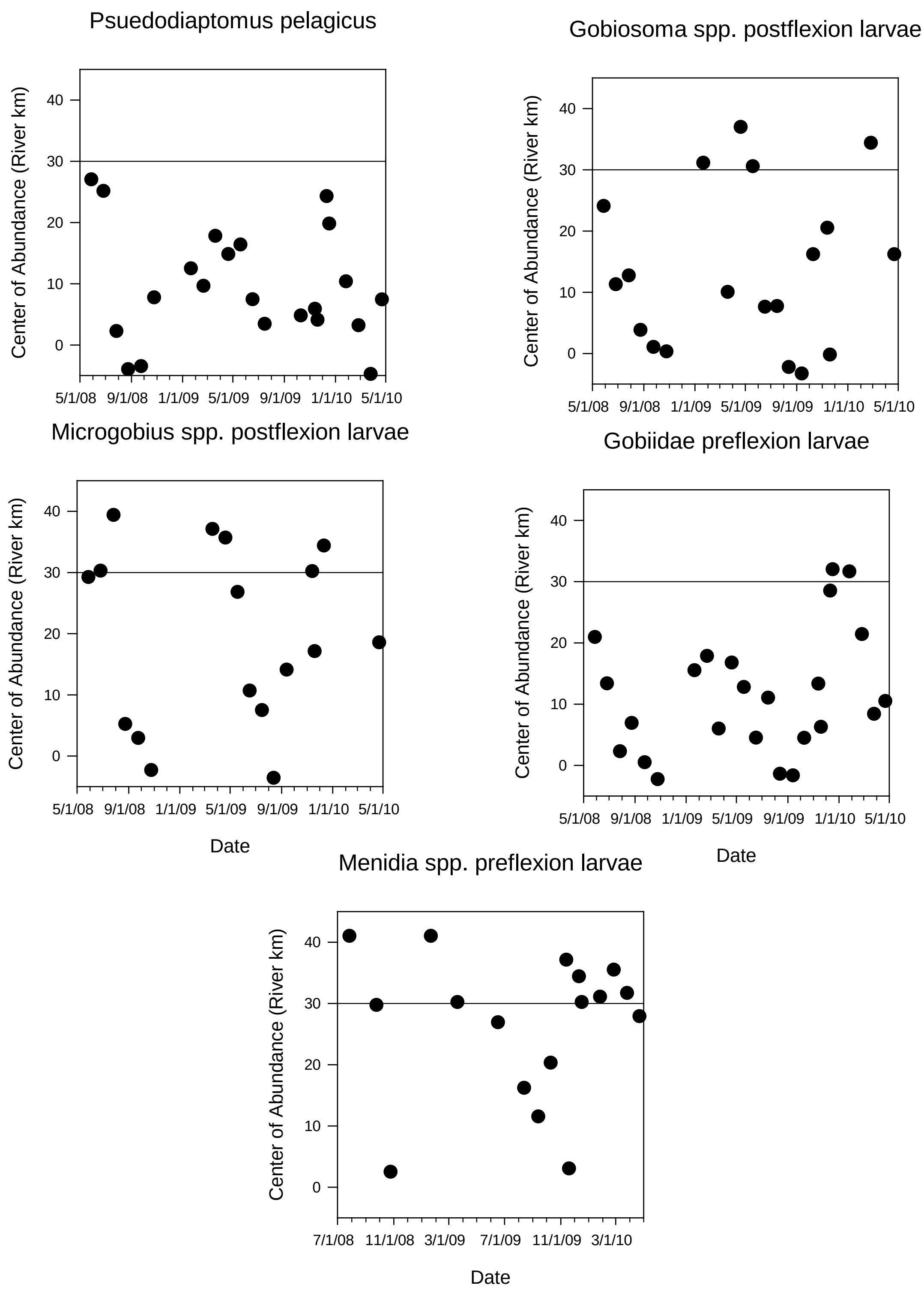


Figure A-28. Continued.

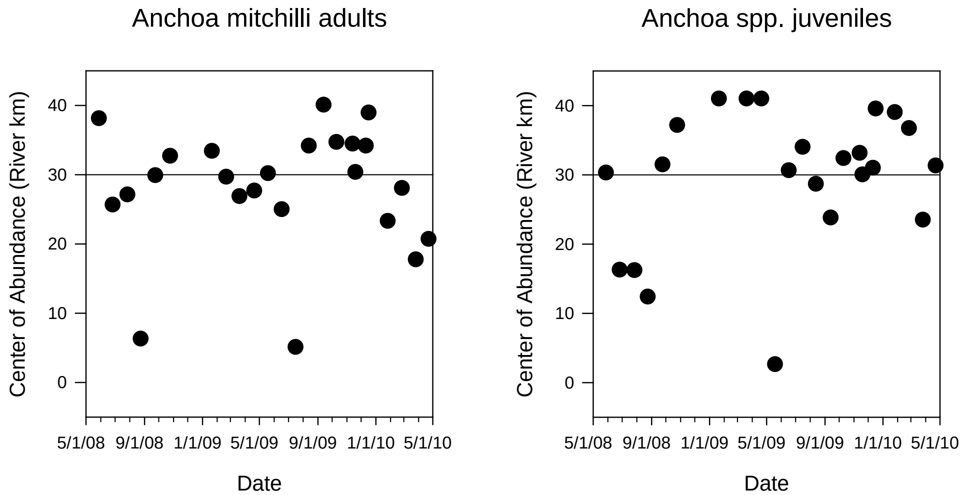


Figure A-28. Continued.

In general, the positions of the 10th and 90th abundance deciles were linearly related to the location of rkm_U the distance-weighted COA (see regressions in **Table A-15**). For *Menidia*, the 10th abundance decile was unrelated to rkm_U so its average position (12.9 km) was employed in calculations of habitat volume. The same situation obtained for *Gobiidae preflexion* larvae but the average position of the 10th decile was -2.3 km and outside the domain of the volume calculations. Neither decile was related to rkm_U for Clytia. Habitat volumes were not calculated for these latter two taxa.

Table A-15. Linear regression relationships between the distance-weighted COA (x) and the location (river km) of the 10th (KM_10) and 90th (KM_90) abundance deciles (y).
(Notes: n is the number of observations, a is the intercept, b is the slope, and r^2 is the coefficient of determination. All regression were statistically significant at $p < 0.05$ except where noted [ns = not significant and * denotes $p < 0.10$].)

Taxon	n	KM_10			KM_90		
		a	b	r^2	a	b	r^2
Clytia spp.	3			ns			ns
Lironeca spp.	16	-5.12	0.417	0.276	3.167	1.155	0.902
Edotia triloba	24	-4.27	0.81	0.759	0.7899	1.163	0.877
Bowmaniensis brasilliensis	23	-4.95	0.625	0.655	4.022	1.115	0.811
Americamysis almyra adults	24	-12.32	1.07	0.796	11.48	0.764	0.828
Americamysis spp. juveniles	24	-12.57	1.04	0.695	15.58	0.669	0.637
Psuedodiapotomus pelagicus	14	-5.73	0.681	0.604	1.099	1.026	0.762
Gobiosoma spp. postflexion larvae	10	-10.3	0.733	0.686	17.17	0.759	0.466
Microgobius spp. postflexion larvae	6	-9.05	0.739	0.554*	4.69	1.05	0.856
Gobiidae preflexion larvae	15			ns	19.8	0.71	0.461
Menidia spp. preflexion larvae	4			ns	4.64	1.05	0.958
Anchoa mitchilli -adults	17	-13.34	1.018	0.489	13.8	0.732	0.833
Anchoa spp. -juveniles	17	-3.38	0.588	0.223	27.3	0.347	0.681

Habitat compression due to translation of rkm_U upstream was assessed graphically (**Figure A-29**). Mysids (*Americamysis*, *Bowmaniella*) exhibited both a shrinking habitat volume and a contracting IDR as rkm_U progressed upstream. For these species, a change in the habitat volume curve was evident between rkm_U of 25 and 30. By contrast, for the isopods (*Lironeca* and *Edotia*) and the copepod (*Pseudodiaptomus*), habitat volume showed curvature. For *Edotia* and *Pseudodiaptomus*, peak habitat volumes occurred when the COA was ~20 km and decreased further upstream despite monotonic expansion of the IDR (**Figure A-29**). For *Lironeca* habitat, volume remained fairly constant to about 30 km where it began to decline with further upstream translation of the COA (**Figure A-29**). The fish taxa exhibited various patterns. Like the mysids, both habitat volume and the IDR decreased as rkm_U moved upstream for the two *Anchoa* groups. The habitat volumes occupied by *Gobiosoma* and *Microgobius* decreased despite an increasing IDR. For both of these species, there is a distinct increase in the slope of the habitat volume curve at an rkm_U of 30 km.

It is noteworthy that taxa exhibiting downward curvature in their habitat volume plots also had monotonically increasing IDRs (*Gobiosoma*, *Microgobius*, *Lironeca*, *Edotia*, and *Psuedodiaptomus*). Such curvature may indicate that at least over part of the range examined (15 to 40 km) increases in dispersion compensated for loss of volume associated with upstream translation of the population. *Menidia* was the only taxon where both habitat volume and IDR increased as rkm_U translated upstream. Increases in dispersion offset decreases in volume associated with geomorphology. The habitat volume plot was also curved indicating a progressive decline in the rate of increase. This decline in the rate of increase may have resulted from the interplay between a constant rate of IDR expansion and an increasing rate of decline in habitat volume associated with the funnel shape of the estuary. The incremental increases in IDR in the upper estuary were less effective at offsetting decreases in habitat volume than in the lower estuary.

The conditional regression model used to evaluate impingement yielded a statistically significant demonstration of impingement for all taxa examined except *Psuedodiaptomus pelagicus* (copepod), *Clytia* (jellyfish), and *Menidia* spp. preflexion larvae. This result does not imply the absence of impingement for these two taxa, but more likely reflects the small number of observations that could be used in the analysis of deciles. The model explained between 40 and 89% of the variation in location of the 90^{th} decile for the remaining taxa. Lagged inflows averaged 22.5 days and ranged between 3 and 60 days (**Table A-16**). Impingement was evident following change point analysis of *Americamysis almyra* (adults) and *Edotia triloba* (**Figure A-29**).

Of the three parameters in the conditional regression model, estimates of threshold inflow had large errors compared to estimates of the constant and slope. In most cases, the 95% confidence intervals bracketing the threshold inflow overlapped zero. Thus, for any one taxon, the river kilometer at which impingement occurs, where position of the 90^{th} decile becomes independent of inflow, was estimated more robustly then the threshold inflow at which impingement begins to occur.

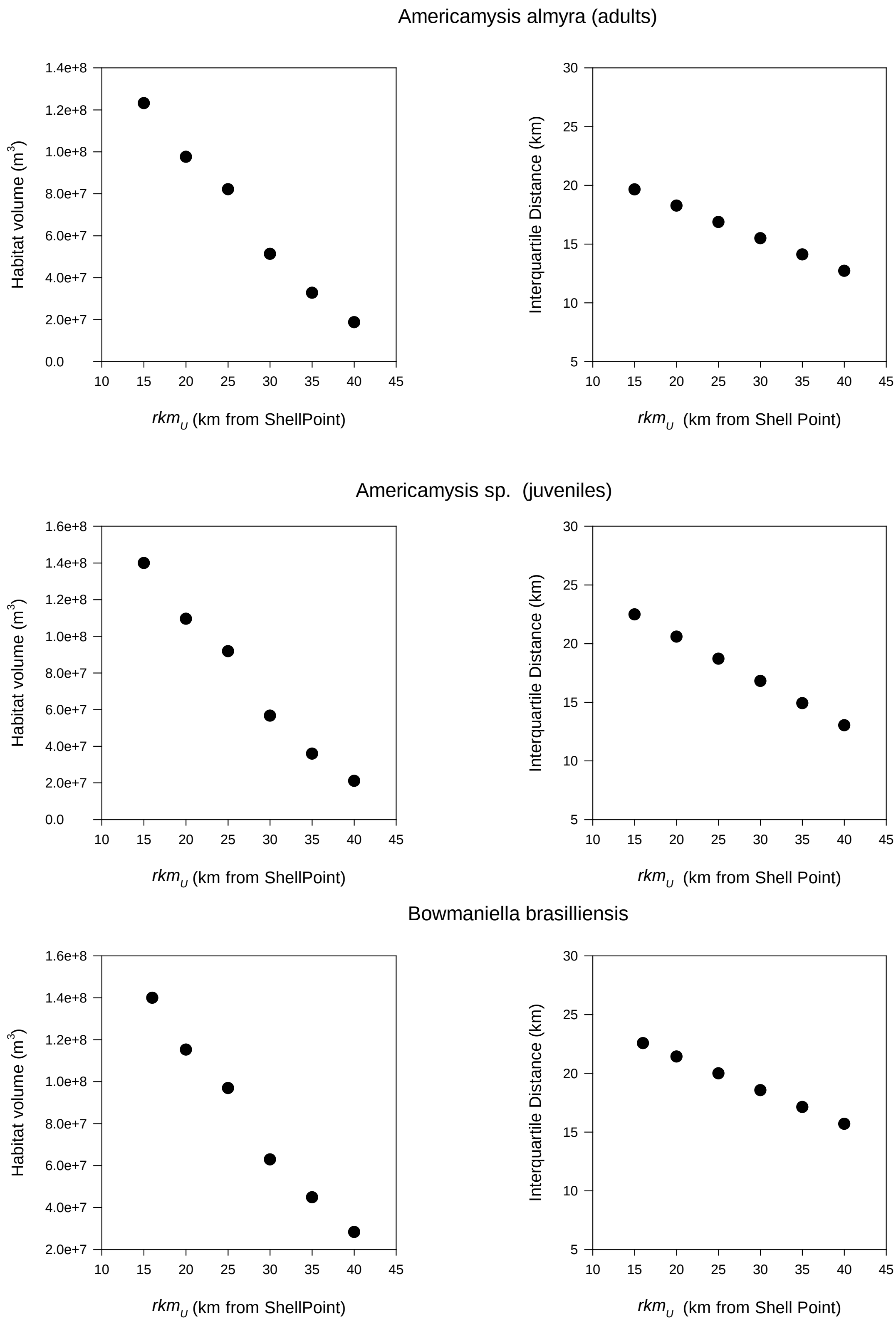


Figure A-29. Potential habitat volume as a function of the position of rkm_U (left) for different taxa. IDR as a function of the position of rkm_U (right).

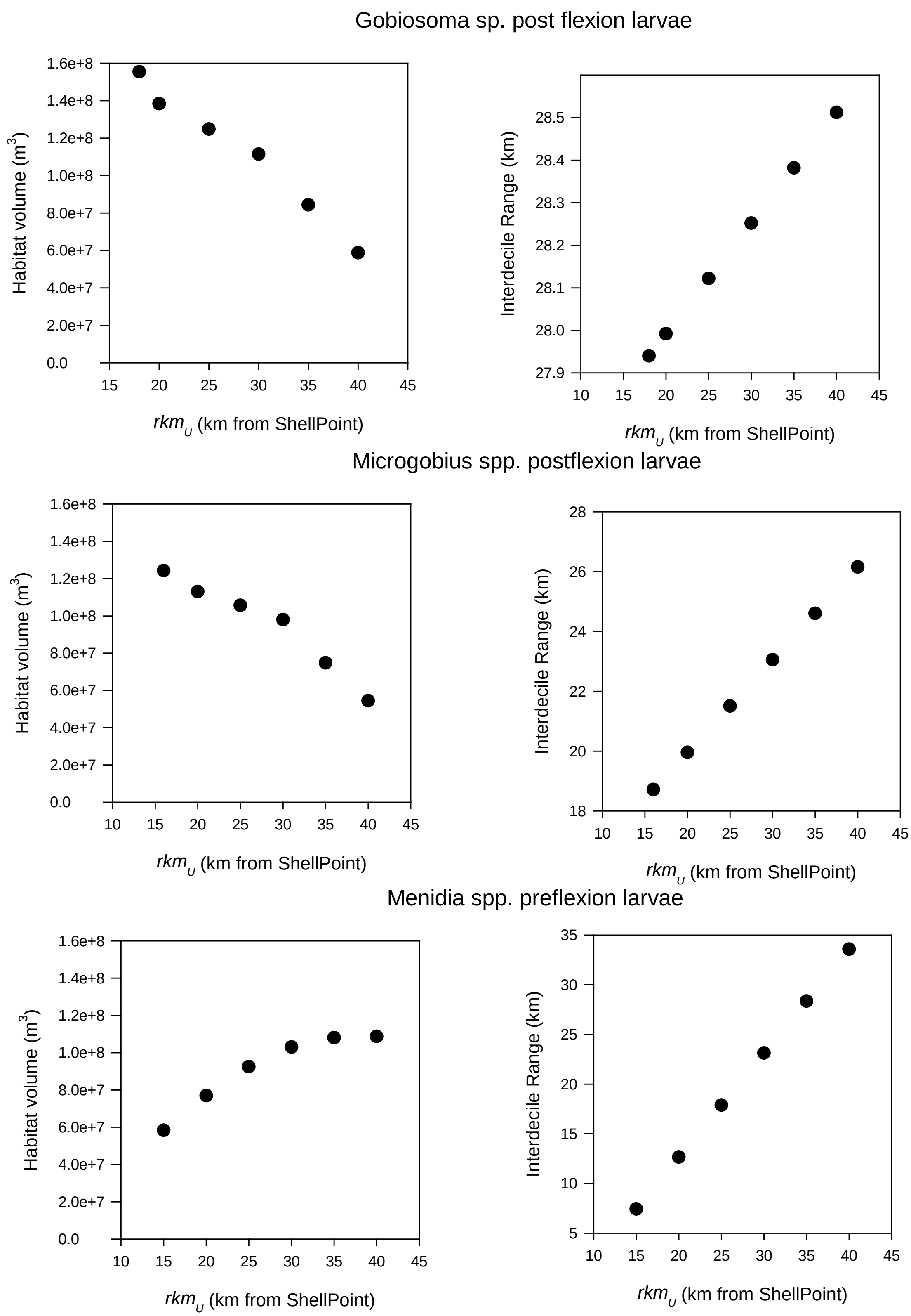
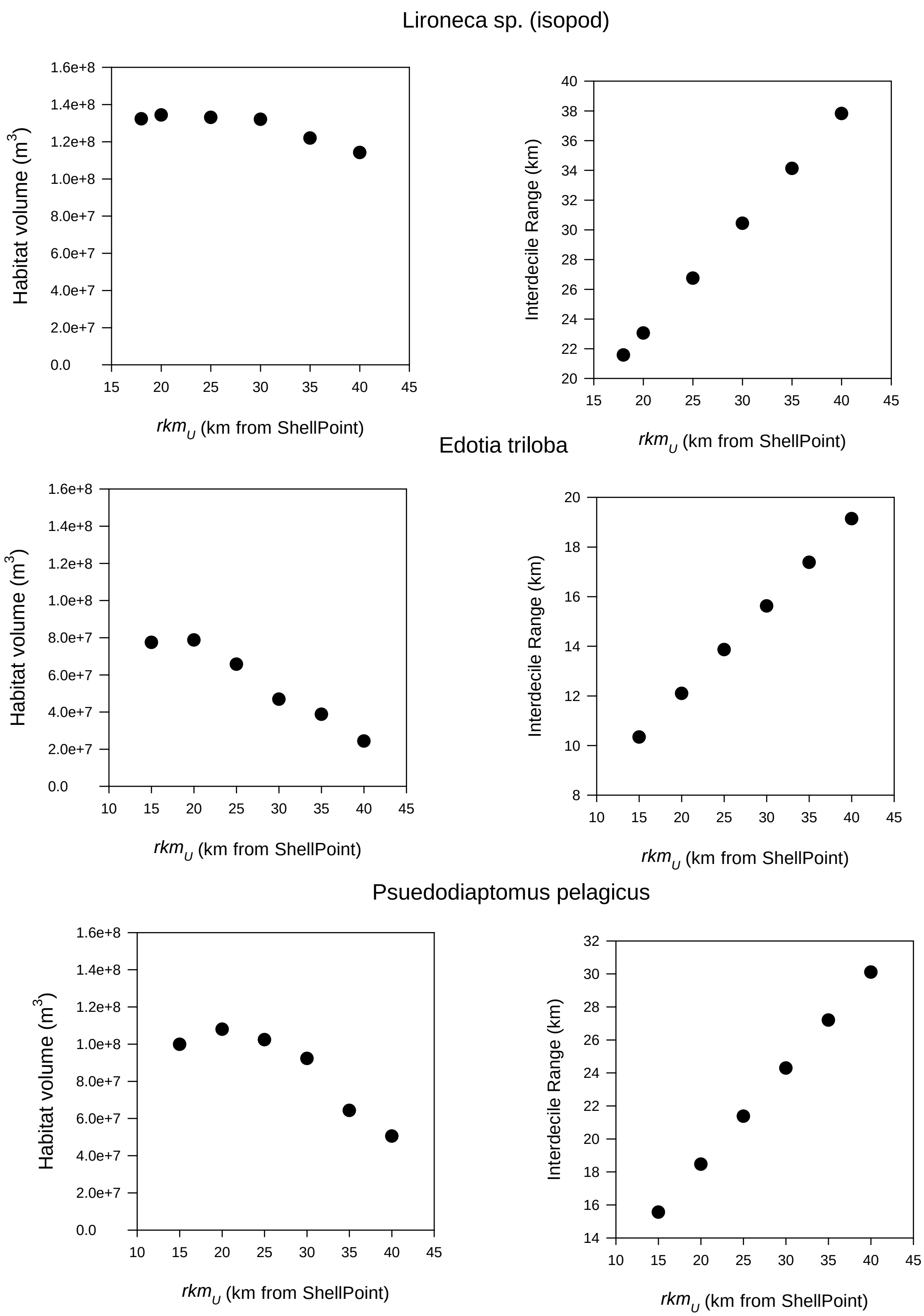


Figure A-29. Continued.



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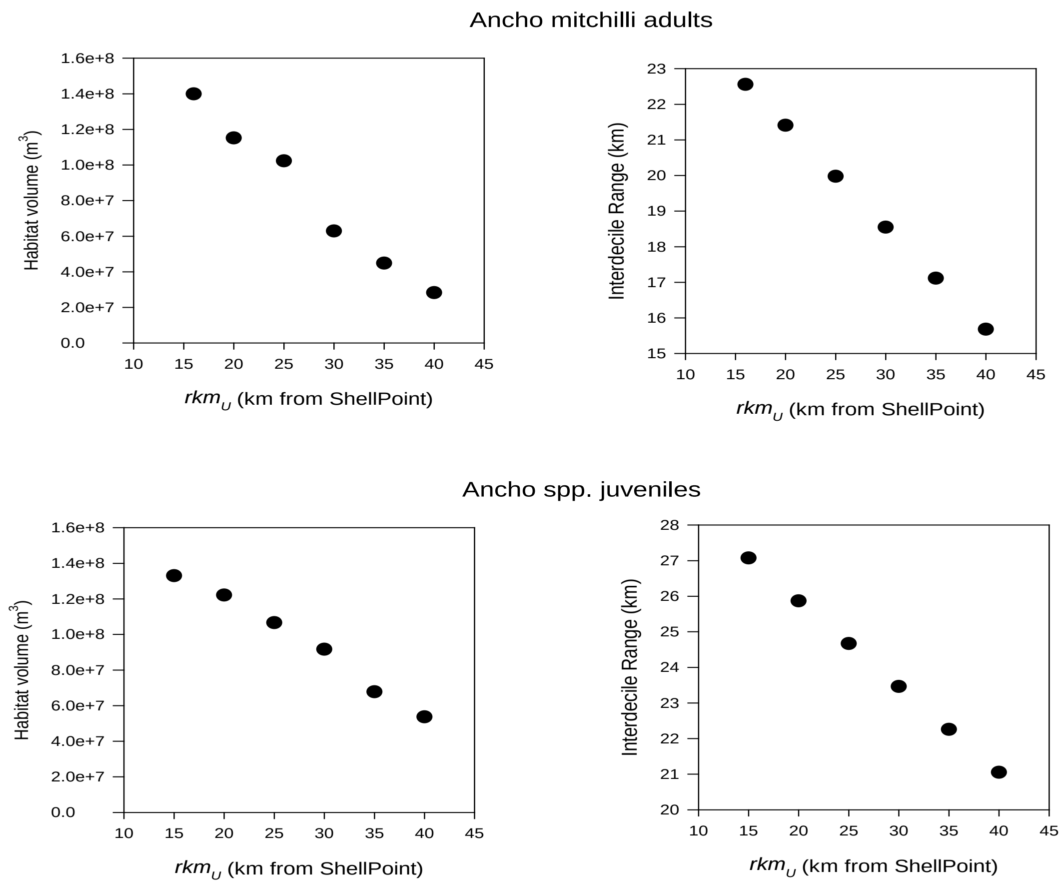


Figure A-29. Continued.

Estimates of threshold inflows for the two *Anchoa mitchilli* groups and Godiidae preflexion larvae were an order of magnitude higher than for other taxa. According to the equations given in Tolley et al (2010), inflows of these magnitudes (2,200–4,200 cfs over 7–30 days) would position the COA for most marine zooplankton far downstream. Results for these taxa were not considered further. Despite the substantial error surrounding any single estimate of threshold inflow, the estimates for the remaining seven taxa were fairly consistent with a mean of 412 cfs (± 40%), a median of 476 cfs and a range of 97.9–565.6 cfs (**Table A-16**). The location at which impingement occurred averaged 34.5 km upstream of Shell Point or about 8 km downstream of S-79.

Impingement was possible if inflow ranged and averaged 98–566 cfs and 412 ± 165 cfs, respectively. Inflows at which habitat compression occurred were less obvious. We do know that the volume of the estuary becomes very much smaller in the narrow region upstream of about river km 30. Almost all taxa investigated (except *Menidia*) experienced habitat compression if the COA was upstream of this point. This position in the river was associated with a clear increase in the rate of habitat compression (*Lironeca*, *Gobiosoma*, and *Microgobius*) or a distinct change in the habitat compression curve (e.g. *Americamysis* and *Bowmaniella;* **Figure A-29**). Inflows associated with an rkm_U of 30 are 125 to 290 based on the median and 75th percentile and about 250 cfs based on the mean (**Table A-14**).

Table A-16. Results of change point analysis to evaluate impingement on the Franklin Lock and Dam (S-79). (Notes: Constant is the river km where the location of the 90th abundance quantile stops changing as inflows decrease, indicating impingement. CP is the inflow at which the 90th decile begins to move downstream as inflow increases. 95% Lower and 95% Upper indicate upper and lower limits of the 95% confidence interval. Decile data for *A. mitchilli* adults were natural log transformed for the analysis. Results for Anchoa and Gobiidae not included in calculation of means and standard deviations.)

Taxon	n	Days	Constant (km)	95%L	95%U	CP (cfs)	95% Lower	95% Upper	beta2	Standard Error	R^2
Clytia spp.	3										
Menidia spp.	4										
Psuedodiaptomus pelagicus	20										
Anchoa mitchilli adults (ln)	17	18	35.51	33.44	37.71	4277.0	4178	4377	-0.0026	0.0294	0.639
Anchoa mitchilli juveniles	19	7	37.79	36.1	39.5	3826.5	-1167	8820	-0.0017	0.000810	0.407
Gobiidae preflexion larvae	15	30	33.36	30.4	36.35	2219.7	-180	4620	-0.0189	0.0227	0.611
Lironeca spp.	16	3	32.18	24.5	39.86	476.3	-1323	2275	-0.0065	0.00188	0.516
Edotia triloba	24	60	31.8	25.7	38	452.1	-1286	2190	-0.0053	0.00168	0.404
Bowmaniella brasilliensis	23	14	29.13	23.3	34.91	512.2	-1041	2065	-0.0064	0.00197	0.454
Americamysis almyra adults	24	14	36.6	34.5	38.7	500.2	-322	1322	-0.0043	0.000572	0.805
Americamysis juveniles	24	14	36	33.5	38.5	565.6	-423	1554	-0.0042	0.000684	0.731
Gobiosoma postflexion larvae	10	45	37.6	23	52.2	97.9	-2615	2811	-0.0058	0.00109	0.783
Microgobius postflexion	6	20	38.1	28.6	47.6	280.2	-1763	2323	-0.0089	0.00209	0.895
			34.49			412.07					
			3.43			164.92					

Addendum to Component Study 4

Gelatinous Predators and Habitat Compression

At least two physical attributes of the CRE may influence the effects of freshwater discharge on zooplankton: its shape and the dam at its head. Despite the alterations that have been made to the CRE, its geomorphology reflects the typical funnel shape of a drowned river valley. The Franklin Lock and Dam (S-79) separates the freshwater Caloosahatchee River from the downstream estuary. The COA of many estuarine plankters has been shown to move downstream as river flows increase and upstream as they decrease (Peebles et al. 2007). At low flows, some organisms will become concentrated in the narrow region of the estuary located more than 30 km upstream of Shell Point. At even lower flows, their upstream progress may be blocked and organisms will be impinged on S-79 located about 43 km upstream of Shell Point (Peebles and Greenwood 2009). The crowding of organisms in a relatively confined space, termed habitat compression (Crowder 1986, Copp 1992, Eby and Crowder 2002), may result in increased predation and competition for limited food resources. In addition, some organisms may be forced to utilize habitat that is physiologically suboptimal and this may result in lower growth and survival (see Petersen 2003).

The purpose of this analysis was to evaluate the potential for overlap between gelatinous predations and potential prey in the narrow region of the estuary upstream of km 30 where habitat compression might occur. Examination of Table 3.7.1.1 in Tolley et al (2010) revealed that for all but one of the 61 taxa examined, the COA moved downstream as discharge increased. Time lags (number of consecutive days prior to sampling used to calculated mean inflow) associated with the responses were variable, but most taxa (92%) responded to inflows averaged over periods of < 2 months, and 32% of the responses corresponded to flows averaged over 6 to 8 weeks. In contrast, the COA for the tanaidacean, *Hargeria rapax*, progressed upstream as flows increased.

At low freshwater inflows, the COA for several taxa occurred (**Table A-17**) in the narrow portion of the upper CRE (> 30 km upstream of Shell Point and < 13 km downstream of S-79). As discussed earlier, this is a region of potential habitat compression where competition and predation may be increased. The presence of two gelatinous (jelly fish) predators, *Clytia* and *Mnemiopsis*, in this region (**Table A-17**) supports the increased predation hypothesis.

Relationships between the location of the COA and freshwater inflow for taxa that occurred upstream of km 30 and, therefore, were likely to experience habitat compression are summarized in **Table A-17**. These relationships have been extracted verbatim from Table 3.7.1.1 in Tolley et al. (2010). The predatory jellyfish, *Clytia*, occurs upstream of km 30 at discharges less than 175 cfs. The comb jelly, *Mnemiopsis*, reaches this location at a discharge of 9 cfs. Habitat compression is unlikely to increase the chances of predation by *Mnemiopsis* except at very low discharges. While habitat compression may still occur for many species, flows greater than 175 cfs should keep the COA of *Clytia* out of the narrow area upstream of km 30, reducing the risk of increased predation.

Table A-17. Response COA (km_U) to freshwater inflow using natural-log transformed inflow values for inflow data recorded at S-79.
(Notes: Regression statistics are sample size [n], intercept, slope, and coefficient of determination r^2 as %. Days is the number of consecutive daily inflow values used to calculate mean inflow. All regressions are significant at $p < 0.04$. The last columns give the calculated discharge at S-79 necessary to position a given taxa 30 km upstream of Shell Point [or 13 km downstream of S-79] at Stations 5D and 5U, respectively.]

Taxon	n	Intercept	Slope	r^2	Days	KM 30 (cfs)
Microgobius spp. postflexion larvae	17	79.3	-8.81	63	55	269
Lironeca sp. (isopod)	24	69.99	-7.84	56	51	164
Gobiosoma spp. postflexion larvae	20	62.12	-7.22	41	57	86
Bowmaniella brasiliensis	24	65.56	-7.2	64	50	140
Pseudodiaptomus pelagicus	22	55.3	-6.9	69	57	39
Menidia spp. preflexion larvae	17	75.09	-6.81	57	67	751
Edotia triloba (isopod)	24	65.25	-6.33	65	51	262
Gobiidae preflexion larvae	24	51.73	-5.94	44	59	39
Americamysis almyra	24	63.51	-5.35	49	51	525
Americamysis spp. juveniles	24	59.76	-5.22	48	50	299
Cumaceans	24	37.13	-4.04	66	48	6
Gobiidae flexion larvae	23	39.45	-4.31	20	66	9
Syngnathus louisianae juveniles	12	37.21	-3.96	53	1	6
Microgobius spp. flexion larvae	18	43	-3.59	26	80	37
Tinectes maculatus postflexion larvae	12	33.48	-2.87	49	2	3
Anchoa mitchilli adult	24	40.01	-1.82	16	17	245
Argulu sp. Branchiuran	16	42.19	-2.39	18	92	164
Median		**55.30**	**-5.35**		**51**	**140**
75%					**59**	**262**
Average					**50**	**179**
Clytia sp.	8	96.03	-12.78	79	50	175
Mnemiopsis spp.	8	35.53	-2.53	88	1	9

Component Study 5: Ichthyoplankton Response to Freshwater Inflow in the CRE

Cassondra Thomas, Christopher Buzzelli and Peter Doering

Abstract

Ichthyoplankton communities are key components of food webs in the upper, oligohaline reaches of most estuaries. This study analyzed historical (1986–1989) data to evaluate effects of salinity and freshwater inflow on ichthyoplankton communities in the CRE. Abundance of ichthyoplankton was greatest when the 30-day inflows at S-79 averaged between 151 and 600 cfs. Juvenile fish appeared to prefer salinities < 10 and their abundance was centered just downstream of Station 2 near Beautiful Island. Flows at S-79 associated with a salinity of 10 near Beautiful Island averaged 237.5+ 255.5 cfs. Flows less than this could result in loss of favorable habitat.

Introduction

Ichthyoplankton (e.g. larval fishes and fish eggs) are a relatively small but vital component of total zooplankton in estuaries (Able 2005, Sutherland et al. 2012). They feed on smaller plankton and serve as a food source for larger animals. Because they swim poorly or not at all, they are sensitive to freshwater inflow (Gillson 2011). Ichthyoplankton assemblages can indicate the status and reproductive potential of adult fish populations in estuaries. This means that when fish such as anchovies and sardines are spawning, ichthyoplankton samples can provide a relative index of population size.

It is important to understand the factors that influence fish populations in small, subtropical estuaries with managed freshwater inflow like the CRE in Southwest Florida (Stevens et al. 2013). Freshwater discharge influences ichthyoplankton location within an estuary and habitat overlap predators (Gillson 2011, Tolley et al. 2012). Additionally, the plankton food sources for fish and decapod larvae (phytoplankton and zooplankton) are also directly impacted by freshwater inflow in the CRE (Chamberlain et al. 2003).

The objective of this research component was to assess the associations between freshwater inflow and ichthyoplankton abundance and community structure in the CRE. Ichthyoplankton data collected between 1986 and 1989 were used in this assessment.

Methods

Nocturnal samples were collected monthly from 1986 to 1989 at six stations within the CRE (**Figure A-30**). Paired 0.5-millimeter conical zooplankton nets with a 505-micrometer mesh were towed obliquely with a flowmeter (meter per second) affixed to one net opening (m^2) to measure the water volume sampled (cubic meters per second). In the laboratory, the samples were sorted to the lowest possible taxonomic level and quantified. They were then grouped into the following categories for analysis: total, eggs, post-yolk sac larval, juvenile, by family, eggs by family, crab, and shrimp. Crabs and shrimp data were included in total ichthyoplankton abundance but not life stage data presentation. Life stage categories were based on Hubbs (1943).

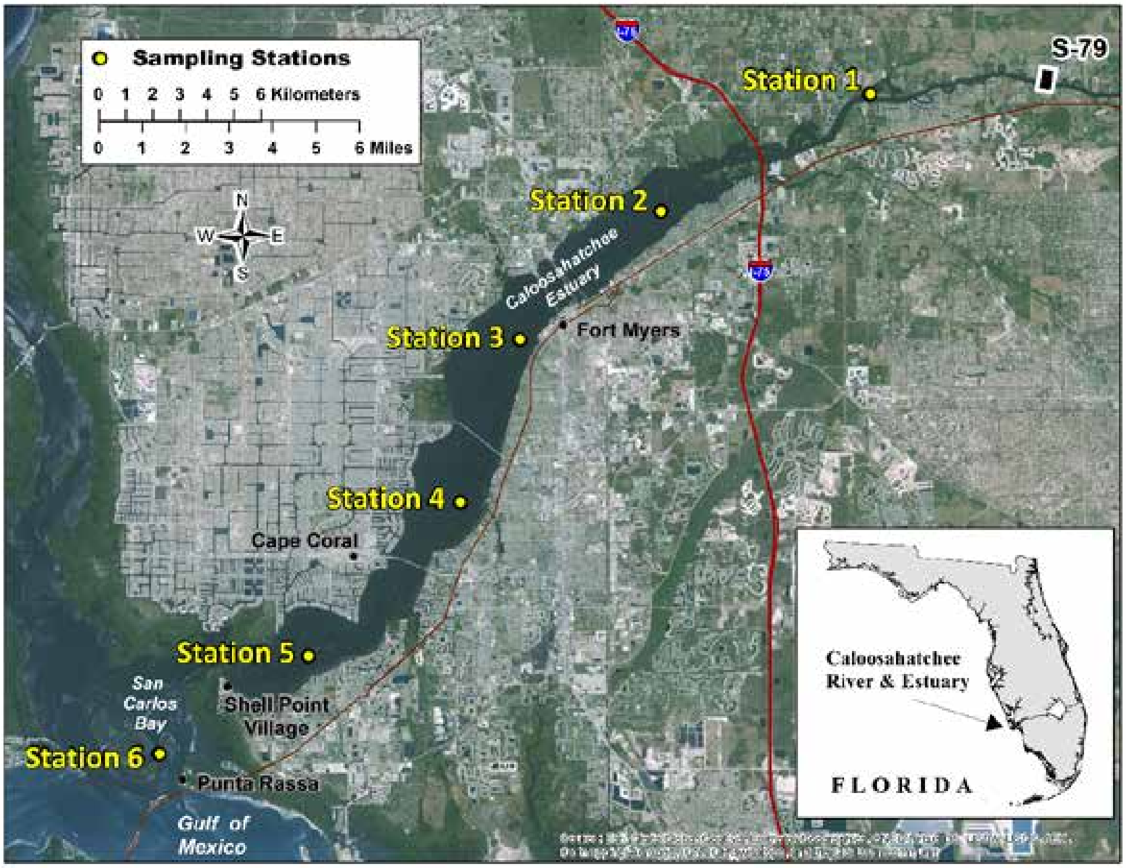


Figure A-30. Map of ichthyoplankton sampling stations from 1986 to 1989 in the CRE.

Freshwater inflow volume to the CRE was measured daily at S-79. Salinity values at each station were predicted using an auto-regressive approach that combined hydrodynamic and time series modeling (Qiu and Wan 2013). Salinities were averaged over 1-, 5-, 7-, 14-, 21-, and 30-day periods prior to the day of sampling. Freshwater inflow was averaged over the same temporal series and grouped into several categories: (1) 0–150 cfs, (2) 151–300 cfs, (3) 301–600 cfs, (4) 601–1,200 cfs, (5) 1,201–2,500 cfs, and (6) > 2,500 cfs following Chamberlain et al. (2003). Due to infrequent sampling events in the second inflow category when averaged over 30 days, Categories 2 and 3 were combined.

The salinity envelop was assessed using the running median of abundance at different salinities. A running median is a smoothing technique that was used to determine the median value of abundance for a particular salinity, and then the median was graphed over all salinities in the data set. This approach removes the influence of outliers and is appropriate when the distribution around the mean is not normal.

Untransformed data were evaluated a priori using principle components analysis and pairwise correlations. Additional statistical analyses included one- and two-way analysis of variance (ANOVA), analysis of covariance (ANCOVA), and nonlinear regressions were performed on log(x+1) transformed abundance data. Tukey's honestly significant difference was used to determine differences between groups. Essential independent variables included sampling station, month, season (dry season is November–April; wet season is May–October), and freshwater inflow category. Interactions detected in two-way ANOVAs were assessed for "clumping" of results (i.e. upper estuary versus lower estuary; lower inflows versus higher inflows; and continuous months). In addition, ANCOVAs were run to test for significance of slope and intercept.

The COA was calculated following Peebles et al. (2007) and Peebles and Greenwood (2009) using **Equation A.10**:

$$rkm_U = \Sigma(\text{km} * \text{U})/\Sigma\ \text{U} \qquad \textbf{\textit{A}.10}$$

where U is the organism's density (#/m^3) at a station and rkm is the distance (km) of the station from the S-79 structure. ΣU is the sum of organism density across all stations for each sampling date. For each sampling date, the quantity (km * U) is calculated for each station. These are summed and divided by ΣU.

Results and Discussion

Total ichthyoplankton abundance most closely correlated to 30-day average inflow and salinity ($p = 0.0002$ and $p < 0.0001$, respectively). Abundance was highest at Stations 5 and 6 ($p < 0.0001$, one-way ANOVA) favoring a more marine ichthyoplankton assemblage (**Figure A-31**). Abundances were greatest when inflows ranged from 151 to 600 cfs ($p < 0.0001$, one-way ANOVA) and declined with increasing freshwater discharge (**Figure A-32**). There were no seasonal signals for total ichthyoplankton or individual taxa.

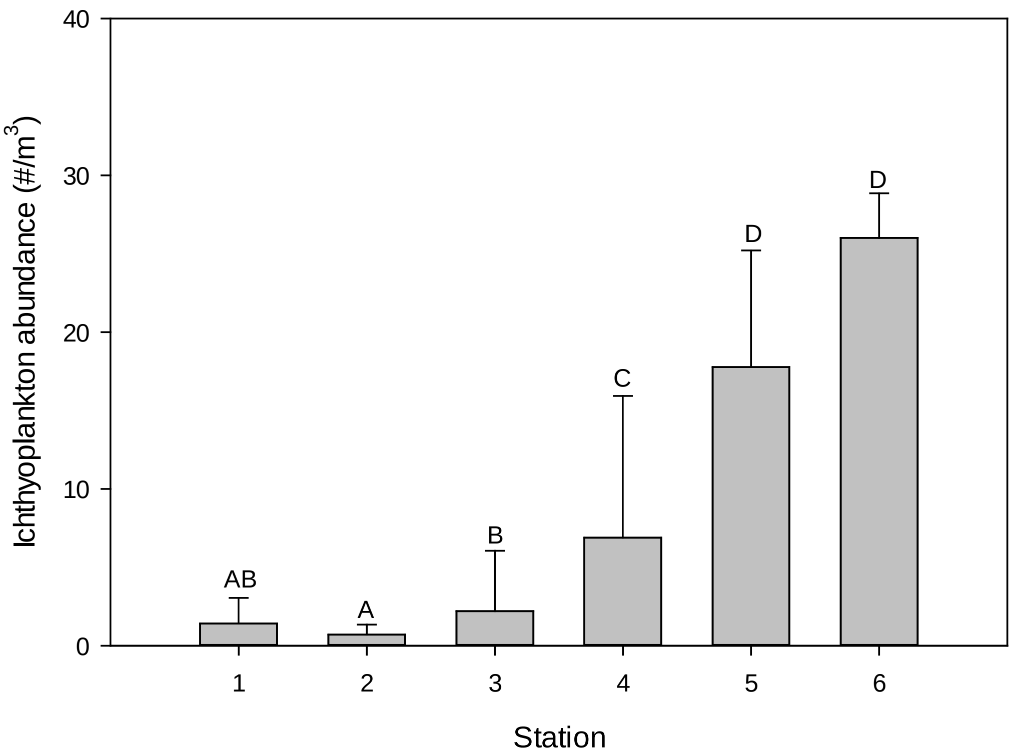


Figure A-31. Ichthyoplankton abundance across stations.
(Notes: Bars with the same letters are not significantly different [p > 0.05].
Data were retransformed from log(x+1) transformed analysis.)

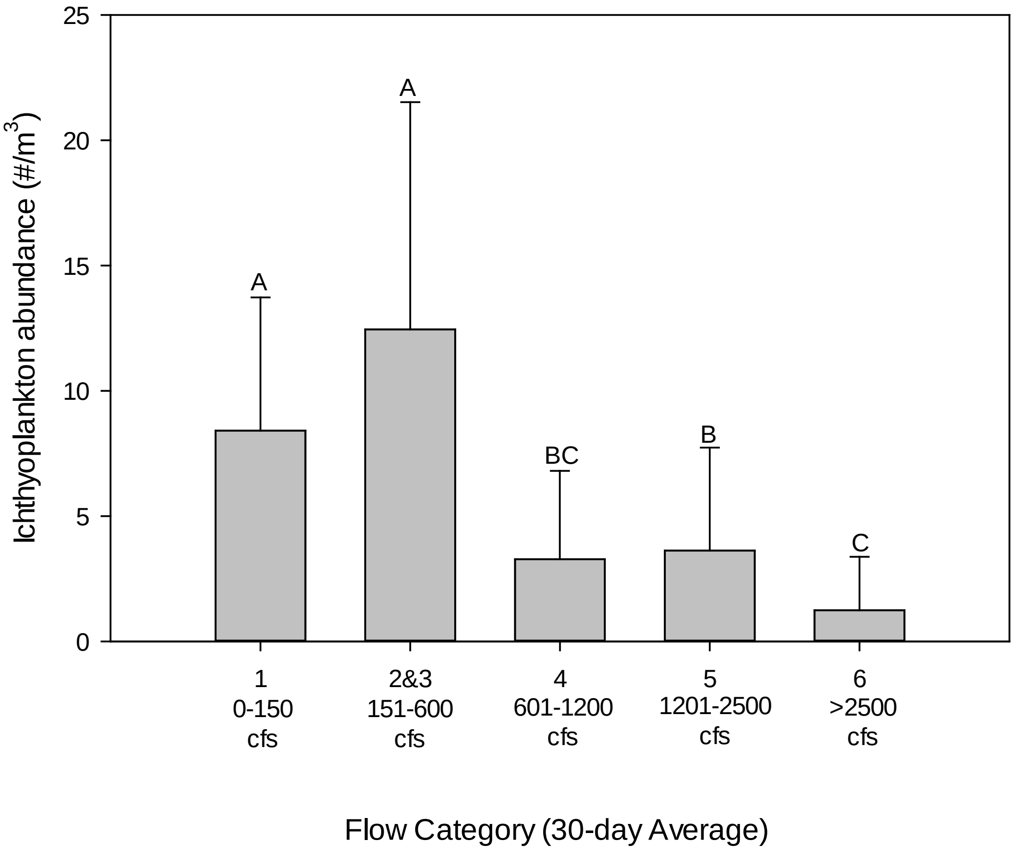


Figure A-32. Ichthyoplankton abundance under different inflow regimes.
(Notes: 1 = 0–150 cfs; 2 and 3 = 151–600 cfs; 4 = 601–1,200 cfs; 5 = 1,201–2,500 cfs; and 6 > 2,500 cfs. The study ran from 1986 to 1989. Bars with the same letters are not significantly different (p > 0.05). Data were retransformed from log(x+1) transformed analysis.)

Although eggs and post-yolk sac larva were primarily located in the lower estuary at high abundances, juvenile fishes were located in the upper estuary regardless of month (**Figure A-33**). This assemblage was dominated by *Anchoa mitchilli* (bay anchovy), which Kimura et al. (2000) noted disperse up-estuary in the Chesapeake Bay to seek lower salinities if the timing of recruitment occurs when salinities are > 18 in the lower estuary. It was likely that those remaining in the downstream estuary did not successfully recruit to the juvenile stage. Thus, the upper estuary is an important nursery for juvenile fish.

Most juvenile fish were found associated with salinities ranging from 0 to 10 (**Figure A-34**). Juvenile fish were most abundant in the upper and mid-estuary. The COA of the juvenile fish ranged from 7 to 30 km downstream of S-79 and averaged 18.9 km (just downstream of Station 2) (**Figure A-35**). Using the density-weighted salinity (S_U) as a covariate, higher inflows result in the COA being located further downstream ($p < 0.0001$, ANCOVA model, $p < 0.0001$ intercept, $p = 0.9024$ slope; **Figure A-35**). These regressions can be used to locate the COA over a range of 30-day average salinity values for particular flow classes. For example, the COA ranged from 7 to 20 km downstream when the S-79 inflow rate was < 600 cfs (lowest flow categories). This result suggested that hydrodynamics were important to the location of the COA, and that juvenile fish location could serve as an indicator for freshwater inflow.

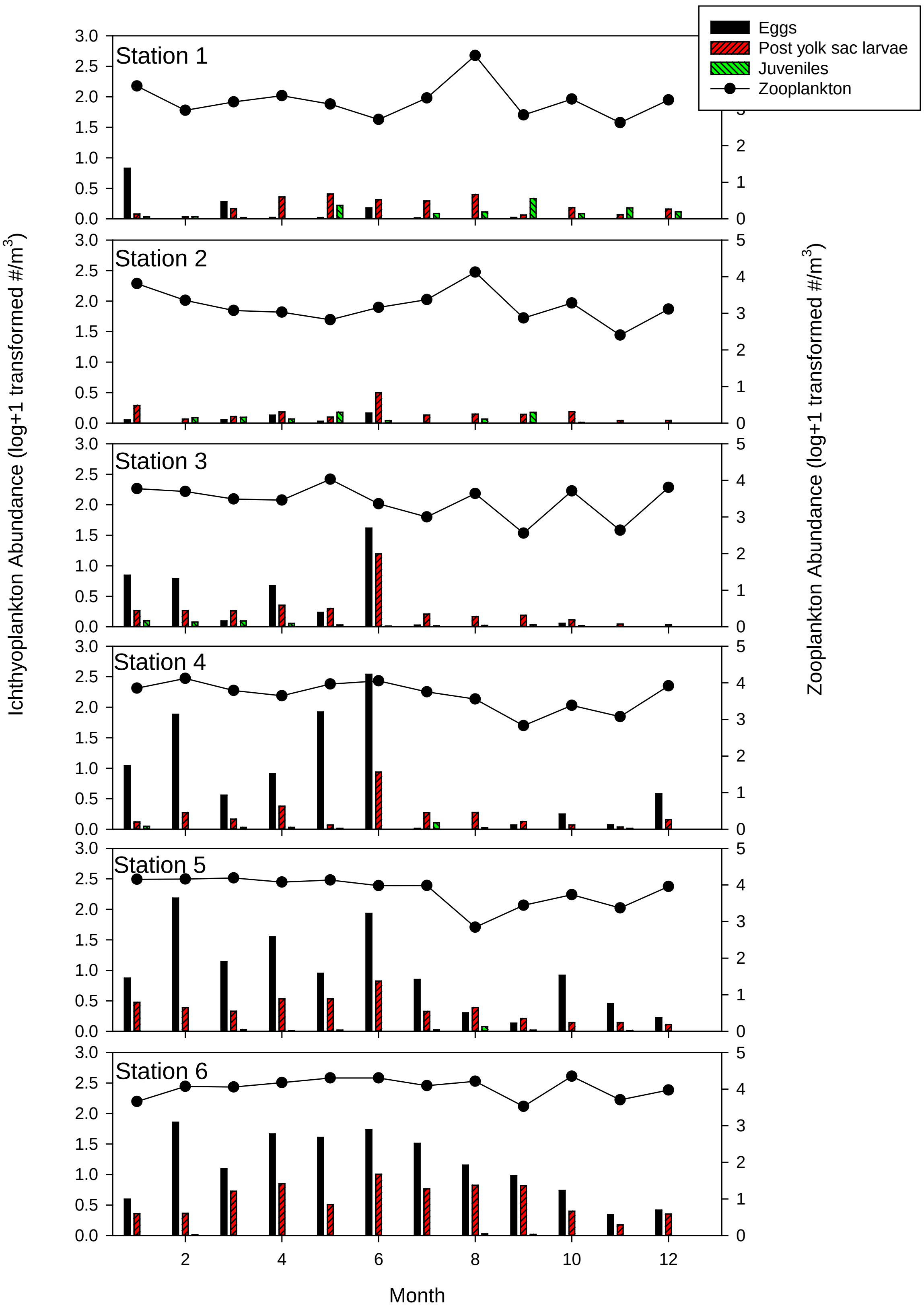


Figure A-33. Ichthyoplankton abundance of different life stages at each station over different months compared to abundance of zooplankton (1986–1989 study).

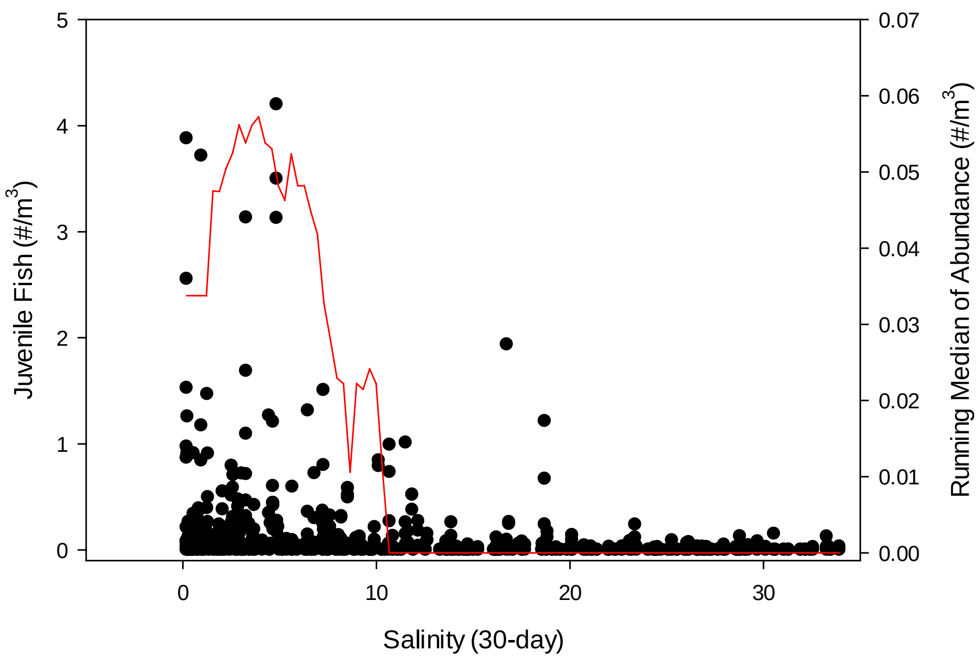


Figure A-34. Juvenile fish abundance relative to 30-day average salinity and the running median of abundance (right axis; red line) to establish a salinity envelope of preference.

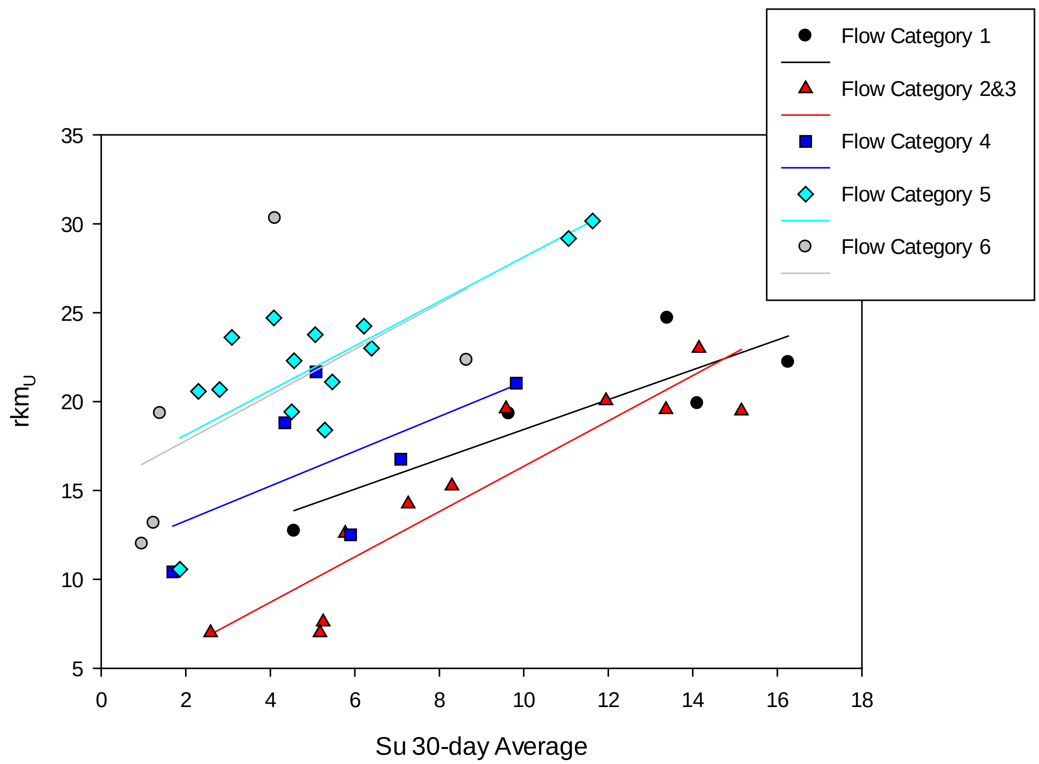


Figure A-35. COA for juvenile fish compared to density-weighted salinity (S_U) at different inflow regimes. (Notes: 1 = 0–150 cfs; 2 and 3 = 151–600 cfs; 4 = 601–1,200 cfs; 5 = 1,201–2,500 cfs; 6 > 2,500 cfs. 1986–1989 study.)

Juvenile fish were most frequently found in salinities ranging from 4 to 6 with frequency of occurrence declining at salinities that were > 10 (**Figure A-36**). Given that the juvenile fish prefer salinity value < 10 and had an average COA just downstream of Station 2, potential habitat loss was assessed by determining the flow at which salinity exceeded 10 at Station 2. Out of the five years of study, there were 11 months where the 30-day average salinity was > 10 at Station 2. The 30-day average inflows associated with these salinity values ranged from 12.3 to 1,357 cfs and averaged 237.5 ± 255.5 cfs. Inflow rates less than this average are likely to result in habitat loss for juvenile fish as the fish need to move upstream toward the S-79 structure to seek their preferred salinity range.

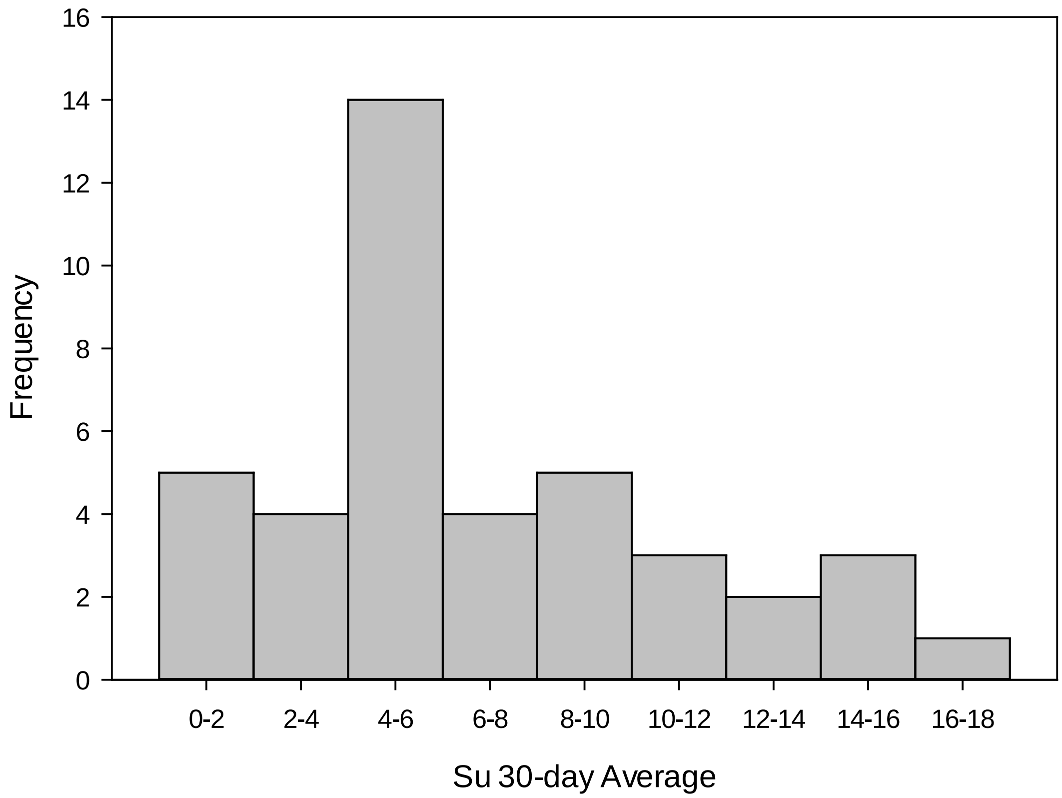


Figure A-36. Frequency distribution of density-weighted salinity (S_U) for juvenile fish.

Component Study 6: Summary and Interpretation of Macrobenthic Community Properties Relative to Salinity and Inflow in the CRE

Christopher Buzzelli

Abstract

The composition, distribution, and density of benthic invertebrate communities (macrofauna) can be used as indicators of salinity and inflow for estuaries. The goal of this study component was to explore the relationships between inflow, salinity, and benthic macrofauna in the CRE. Benthic samples were collected every 2 to 4 months at seven stations during two periods (February 1986–April 1989 and October 1994–December 1995). The abundance, diversity, and composition of the macrofaunal community were determined relative to observed fluctuations in salinity. Four distinct zones emerged based on salinity ranges and the composition of the macrobenthic community. Conditions conducive to maintain the characteristic community observed during the sampling periods in the most upstream zone (salinity = 0 to 4 and 0 to 7 km from S-79) occurred on 54% of dry season days from 1993 to 2012. The indicator inflows (Q_I) ranged from 0 to 3,720 cfs and averaged 501 ± 525 cfs for the days where salinity was 3 to 4 (n = 181).

Introduction

Alterations to the quality, quantity, timing, and distribution of inflows are extremely important to the health and function of an estuary (Montagna et al. 2013). Within the CRE, changes in freshwater inflows have altered salinity regimes and the ecology of the estuary (Chamberlain and Doering 1998a, Barnes 2005). Changes in freshwater inflows and salinity have been shown to change the distribution and dynamics of many taxa and communities in the CRE including submersed vegetation (Doering et al. 2001, 2002, Lauer et al. 2011), oysters and dermo disease (La Peyre et al. 2003, Barnes et al. 2007, Volety et al. 2009), fauna inhabiting oyster reefs (Tolley et al. 2005, 2006), and fishes (Collins et al. 2008, Heupel and Simpfendorfer 2008, Stevens et al. 2010, Simpfendorfer et al. 2011, Poulakis et al. 2013).

Benthic organisms are ideal biological indicators of changes in water quality because they have limited mobility, long lifespans relative to plankton, and sensitivity to changes in water and sediment quality (Montagna et al. 2013). Many studies have used benthic communities as indicators of freshwater inflow and estuarine status (for a summary see Montagna et al. 2013). Macrobenthic communities have been used as indicators in Rincon Bayou, Texas (Montagna et al. 2002b) and other Texas estuaries (Palmer et al. 2011), Southwest Florida (Montagna et al. 2008, Palmer et al. 2011), and the St. Johns River Estuary in northeastern Florida (Mattson et al. 2012).

The goal of this research component was to explore the relationships between freshwater inflow, salinity patterns, and the distribution, density, and composition of benthic macrofaunal communities in the CRE (Montagna and Palmer 2014). This assessment was based on a more comprehensive analysis of macrofaunal communities and salinity patterns in the CRE (Montagna and Palmer 2014). Specifically, this effort emphasized the potential effects of reduced dry season inflow on salinity patterns in the upper CRE.

Methods

The study was designed by Robert Chamberlain, SFWMD, to investigate benthic macrofauna distributions as a function of salinity and to compare variability between dry (November–April) and wet (May–October) seasons. Benthic samples were collected at seven stations (B1–B7; **Figure A-37A**) during two periods: from February 1986 to April 1989 (Period 1) and from October 1994 to December 1995 (Period 2). Sampling occurred every two months at Stations 1 through 6 and every four months at Station 7 during Period 1. Four stations (2, 4, 5, and 6) were sampled in Period 2 for 12 of 15 months. The environmental conditions were different between the two sampling periods. While relatively low inflow rates characterized Period 1, extremely high inflow rates occurred during Period 2.

Benthic samples were collected using a Wildco® petite ponar grab (0.02323 m^2). Five replicates were collected at each station within a 30–50-m diameter. The sediment at each station consisted of predominantly sand and shell hash. Samples were sieved in the field on a 500–micrometer screen, preserved in formalin buffered by Epsom salt, and stained with Rose Bengal. Invertebrates were separated from the sieved substrate by either SFWMD (Period 1) or Mote Marine Laboratory (Period 2) and stored in ethanol. Staff from Mote Marine Lab identified the dominant taxa (95% of organisms) to the species level and the remaining taxa to genera or higher taxa groups.

Salinity values along the length of the CRE from 1980 to 2000 were estimated using a time series modeling technique that accounted for spatial distribution of salinity in the estuary and driving factors such as freshwater inflows, rainfall, and tide (Qiu and Wan 2013). This model output has been calibrated to local salinities and uses a linear reservoir model to simulate Tidal Basin flows (Wan and Konyha 2015).

Macrofaunal diversity was calculated using Hill's N1 diversity index because it has units of number of dominant species (Hill 1973). Differences in macrofauna characteristics among stations were tested on two subsets of the data because the sampling design was uneven. The first subset included all seven stations for ten months in Period 1 (dry season only). The second subset included four stations (2, 4, 5, and 6) across all months (except November 1987) and encompassed both sampling periods. Differences in macrofauna characteristics among stations were determined using two-way ANOVA with station and month-year as treatments. A linear contrast was added to the ANOVA on the second subset (four stations and all dates) to test for differences among sampling periods. Post-hoc Tukey tests were run to test for differences among stations and station-period interactions.

Macrofaunal community structure was analyzed using non-metric multi-dimensional scaling (MDS) using a Bray-Curtis similarity matrix among stations to create a MDS plot (Clarke 1993, Clarke and Warwick 2001). Relationships within each MDS were highlighted through cluster analysis using the group average method. Significant differences between each cluster were tested with the SIMPROF permutation procedure with a significance level of 5% ($p = 0.05$). Where stations were sampled in both time periods, differences in community structure and species assemblages between periods and among zones were tested using ANOSIM and SIMPER in Primer (Clarke 1993). Data were $\log_e(x + 1)$ transformed prior to multivariate analysis to decrease the effect of numerically dominant species on community composition (Clarke and Gorley 2006). This information was used to help characterize salinity zones for the CRE in both dry and wet seasons.

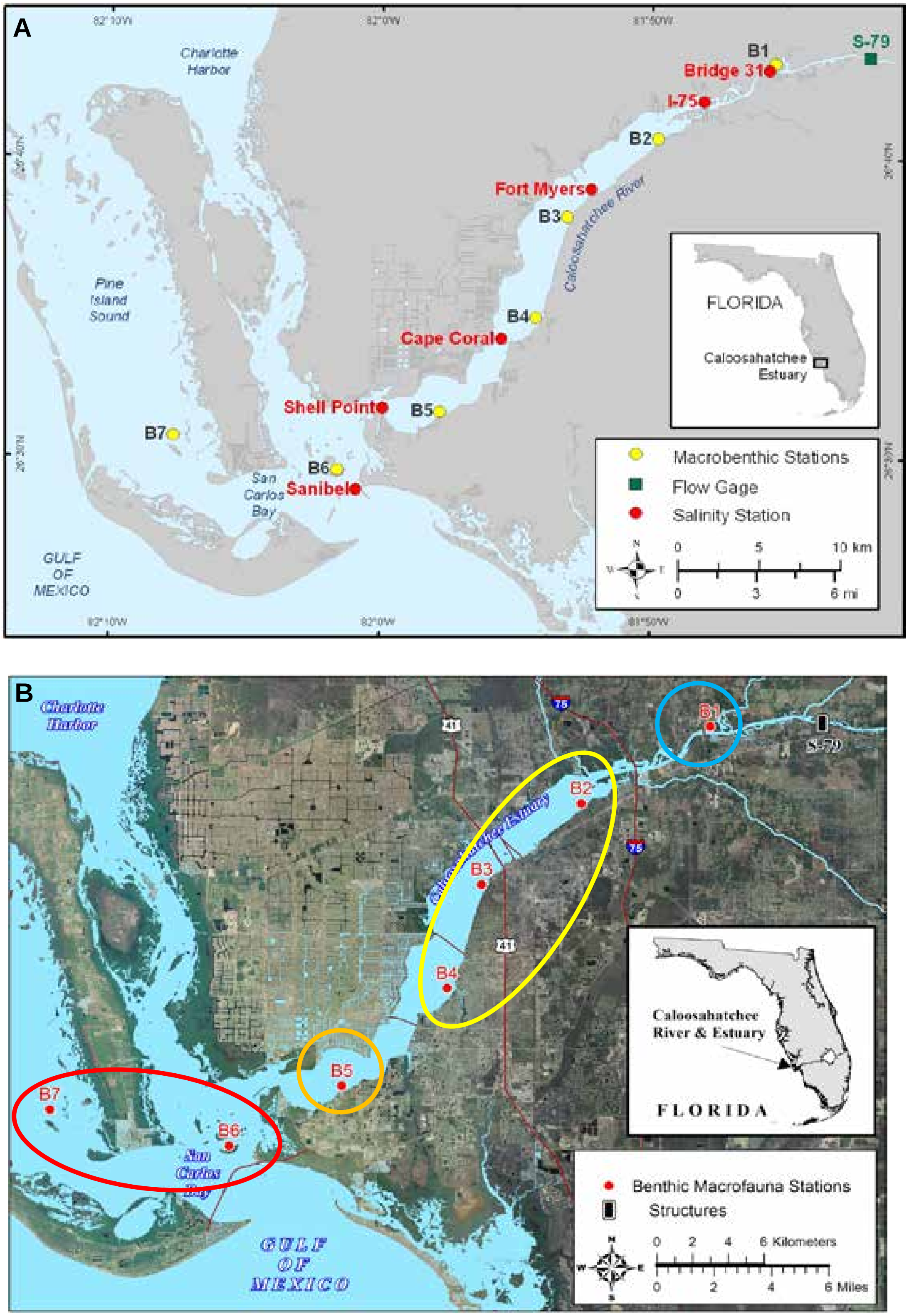


Figure A-37. (A) Location map for macrobenthic sampling in the CRE. (B) Map of the CRE with the macrobenthic sampling stations (B1 through B7; red) and four estuarine zones determined in this study. (Included in map A are sampling macrobenthic stations [B1 through B7; yellow], the long-term salinity stations (red), and the upstream location of freshwater inflow [S-79; green]).

The benthic community in the uppermost CRE (0–7 km from S-79) should be most sensitive to reduced freshwater inflow. Salinity responds quickly to changes in discharge in this part of the estuary. Changes in the number of low salinity species indicate a change in hydrologic conditions. The MDS analysis provided a target salinity range of 0–4 for the macrobenthic communities in the upper CRE (Montagna and Palmer 2014). Thus, salinities > 4 may lead to changes in the oligohaline benthic community.

Long-term salinity data collected at Bridge 31 (BR31) in the upper CRE was used to assess estuarine conditions for macrofauna communities in the most upstream portion of the estuary (**Figure A-37A**). Average daily salinity at this location from January 22, 1992, to August 16, 2012, was merged with average daily freshwater inflow at S-79. These data were categorized by water year and season (dry versus wet) with analyses focused on the dry season days throughout the POR. The number and percentage of dry season days where salinity values ranged from 0 to 1, 1 to 2, 2 to 3, and 3 to 4, and > 4 were calculated along with the averages and standard deviations for salinity and freshwater inflow associated with each of these salinity classes. The freshwater inflows on the days where salinity was assumed to be the highest level tolerated by the expected macrofauna species (salinity = 3 to 4) were queried from the data set. The range and average and standard deviation of associated freshwater inflows were calculated from these selected days.

Results and Discussion

There was clear zonation of benthic communities along the salinity gradient in the CRE (**Figure A-37B**). This zonation was evident when comparing N1 diversity and multivariate community structure of the communities along the length of the CRE. The positive relationship between salinity and diversity on a spatial salinity gradient is common in many estuaries due to the increasing abundance of marine species in downstream locations (Whitfield et al. 2012).

In the current study, 34 taxa were identified as being indicators of salinity (**Table A-18**). Two taxa served as indicators of limnetic conditions (salinity < 0.5), 6 taxa indicated oligohaline conditions (salinity 0.5 to 5), 11 indicated mesohaline conditions (salinity 5 to 18), 10 indicated polyhaline conditions (salinity 18 to 30), and 5 provided an indication of euhaline conditions (salinity 30 to 40) according to the Venice salinity classification system (**Table A-18**; Anon 1958, Cowardin et al. 1979).

Table A-18. Summary of dominant macrobenthic taxa and relationship with salinity in the CRE. (Notes: Abundance is reported in number of individuals per meter square [# m^{-2}]. Source: Montagna and Palmer 2014.)

Taxa Name	Higher Taxa Group[1]	Lower Taxa Group[2]	Parameters					p Value
			a (Peak Abundance)	b (Skewness)	c (Salinity)			
					Estimate	90% Low	90% High	
Ceratopogonidae sp.	Insecta	Diptera	29	3.93	0.0	-1.7	1.8	0.0364
Amphicteis floridus	Polychaeta	Ampharetidae	137	2.10	0.4	-0.3	1.0	< 0.0001
Edotia sp. 1	Crustacea	Isopoda	546	1.16	0.8	0.5	1.2	0.0008
Edotia spp.	Crustacea	Isopoda	253	1.53	1.0	0.2	1.7	0.0016
Tellina texana	Bivalvia	Veneroida	1,139	-1.38	1.6	0.5	2.7	0.0002
Tubificidae w/o cap. setae	Clitellata	Oligochaeta	1,034	1.94	1.9	0.6	3.2	< 0.0001
Neanthes succinea	Polychaeta	Nereididae	109	1.26	2.2	0.0	4.3	0.0131
Streblospio benedicti	Polychaeta	Spionidae	970	1.48	2.7	1.0	4.4	< 0.0001
Eteone heteropoda	Polychaeta	Phyllodocidae	128	0.68	5.2	3.2	7.2	0.0022
Assiminea succinea	Gastropoda	Neotaenioglossa	6.2×10^{10}	-0.04	5.9	5.1	6.8	< 0.0001
Mulinia lateralis	Bivalvia	Veneroida	1,347	-0.65	6.8	0.6	13.0	0.0772
Tellina versicolor	Bivalvia	Veneroida	16,711	-0.09	7.0	6.7	7.2	< 0.0001
Stylochus sp.	Platyhelminthes	Polycladida	51	0.77	8.8	5.7	11.8	< 0.0001
Tagelus plebeius	Bivalvia	Veneroida	57,497,727	-0.04	10.1	9.9	10.2	< 0.0001
Ischadium recurvum	Bivalvia	Mytiloida	1,016,692	0.05	10.1	9.7	10.5	< 0.0001
Lucina nassula	Bivalvia	Veneroida	36	-0.63	13.0	-3.1	29.1	0.0075
Ampelisca spp.	Crustacea	Amphipoda	3,469	0.36	15.0	12.1	17.9	0.0003
Paraprionospio pinnata	Polychaeta	Spionidae	290	0.95	15.8	9.5	22.1	< 0.0001
Mysella sp. A	Bivalvia	Veneroida	1,828	-0.04	17.0	16.7	17.4	0.0063
Odostomia sp.	Gastropoda	Heterostropha	220	0.11	20.4	19.9	21.0	0.0032

Table A-18. Continued.

Taxa name	Higher Taxa Group[1]	Lower Taxa Group[2]	Parameters: a (Peak Abundance)	b (Skewness)	c (Salinity) Estimate	c (Salinity) 90% Low	c (Salinity) 90% High	p Value
Mysella planulata	Bivalvia	Veneroida	115	0.35	21.5	14.2	28.7	0.0302
Caecum pulchellum	Gastropoda	Neotaenioglossa	124	0.10	21.7	20.2	23.1	0.0067
Aglaophamus verrilli	Polychaeta	Nephtyidae	22	0.58	23.5	8.7	38.4	0.001
Phascolion strombus	Sipuncula	Golfingiiformes	119	0.15	24.8	22.7	26.9	0.0211
Listriella barnardi	Crustacea	Amphipoda	864	-0.04	26.0	24.1	27.2	0.0005
Parvilucina multilineata	Bivalvia	Veneroida	51	0.24	26.1	23.8	28.4	< 0.0001
Ampelisca sp. 3	Crustacea	Amphipoda	153	0.15	26.5	23.7	29.3	0.004
Sthenelais sp. A (or spp.)	Polychaeta	Sigalionidae	72	0.23	26.9	22.4	31.3	0.0015
Kalliapseudes sp. 1	Crustacea	Tanaidacea	188	0.12	27.6	26.4	28.9	0.0012
Schistomeringos rudolphi	Polychaeta	Dorvilleidae	103	0.03	30.1	29.7	30.4	0.0041
Spiochaetopterus oculatus	Polychaeta	Chaetopteridae	425	0.01	30.7	30.3	31.1	0.001
Molgula occidentalis	Ascidiacea	Pleurogona	519	-0.03	31.4	31.1	31.8	0.0006
Eusarsiella texana	Crustacea	Ostracoda	310	-0.03	31.6	31.2	32.1	< 0.0001
Grubeulepis mexicana	Polychaeta	Eulepethidae	110	0.04	32.1	31.8	32.5	0.027

While the Venice system is widely used to divide an estuary into salinity-based zones, it is not biologically relevant in all cases. It is often more practical to divide an estuary into several overlapping zones that are based on the abundances of organisms along a salinity gradient (Bulger et al. 1993). This study applied a combination of these two classification schemes to specify four zones to describe the distribution and composition of macrobenthic communities in the CRE (**Table A-19**). These zones, based on dry season salinities, were designated Bulger Zone 1 (salinity of 0.2–4.2), oligohaline zone 2 (2.6–12.5), mesohaline zone 3 (15.1–24.9), and polyhaline zone 4 (28.0–34.7).

Table A-19. Seasonal ranges for salinity zones in the CRE based on classifications provided by Bulger et al. 1993.

Zone	Dry	Wet
Bulger Zone 1	0.2–4.2	0.2–0.2
Oligohaline	2.6–12.5	0.2–3.1
Mesohaline	15.1–24.9	7.9–13.9
Polyhaline	28.0–34.7	21.0–30.5

Despite the loss of several macrobenthic species in high flow relative to low flow periods, the abundance of several mobile invertebrates and fish have been documented to decrease during low flow periods in Southwest Florida estuaries (Flannery et al. 2002). Mobile species with decreases during low flow periods include bay anchovy and sand seatrout juveniles, mysids, and grass shrimp. A previous study on fish and mobile aquatic invertebrates (blue crab [*Callinectes sapidus*] and pink shrimp [*Farfantepenaeus duorarum*]) separated the CRE into three zones, with the lower, middle and upper zones incorporating the reach of the benthic stations in the current study of stations 4 and 5, 2 and 3, and 1, respectively (Stevens et al. 2010).

Salinity observations at BR31 from WY1993–WY2012 provided a platform to explore long-term, dry season variations in inflow and salinity conditions in the Bulger Zone (0.2 to 4.2; **Figure A-38A** and **Table A-20**). Average dry season salinity varied from 0.3 (WY1995) to 13.3 (WY2001) averaging 4.5 ± 4.8 over all dry season days (n = 3,591). Periods of reduced salinity coincided with increased inflows in the dry seasons of WY1994–WY1996, WY1998, and WY2003–WY2006. The percentage of dry season days where salinity was within the desired range indicative of the Bulger Zone as defined for macrobenthic communities ranged from 0.0% (WY1997, WY2001, WY2007, and WY2008) to 96–99% (WY1995 and WY2003–WY2006; **Figure A-38B**). Salinity was within the desired 0 to 4 range on ~54% of dry season days at BR31 with percentages of 38.7, 5.8, 4.6, and 5.0 for the 0–1, 1–2, 2–3, and 3–4 salinity categories, respectively (**Table A-20**). This means that salinity values were in excess of 4 on ~46% of the dry season days. The inflow rate ranged from 0 to 3,720 cfs and averaged 501 ± 525 cfs for the days where salinity was 3 to 4 (n = 181).

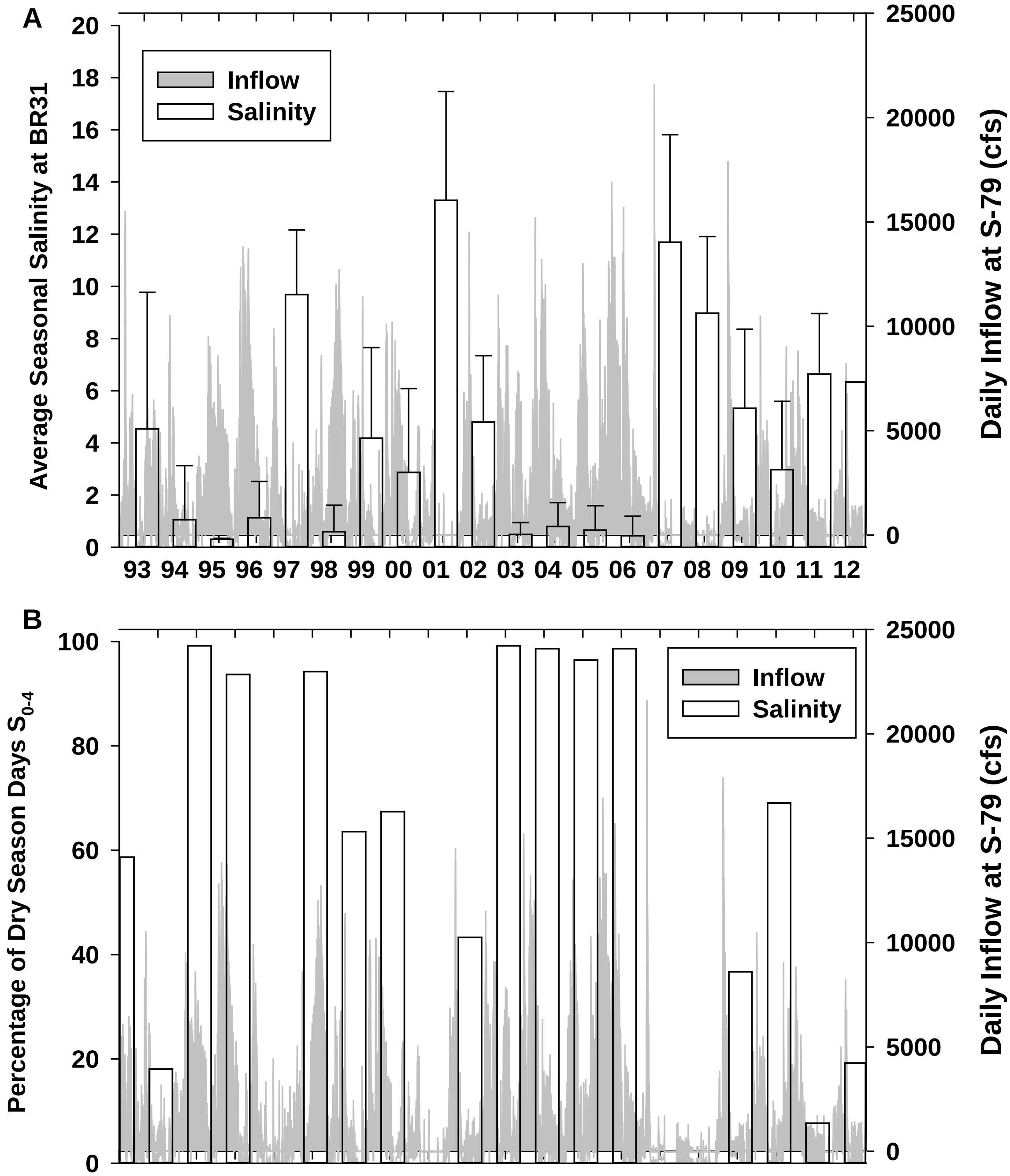


Figure A-38. (A) Long-term average salinity in the dry season at BR31 in the upper CRE (open bars; left axis) superimposed on daily freshwater inflow at S-79 (grey fill; right axis). (B) The percentage of dry season days where salinity ranged from 0 to 4 (S_{0-4}) at BR 31 in the upper CRE (open bars; left axis) superimposed on daily freshwater inflow at S-79 (grey fill; right axis).

Table A-20. The number and percentages of dry season days for average daily salinity values at BR31 over a series of salinity class criteria (0 to 1, 1 to 2, 2 to 3, 3 to 4, > 4, and all dry season days) from WY1993 to WY2012.

Salinity Class	Number	Percentage (%)	Salinity	Inflow S-79 (cfs)	
			Avg ± SD	Range	Avg ± SD
0 to 1	1,388	38.7	0.3 ± 0.2	0 to 15,700	3,074 ± 2,777
1 to 2	208	5.8	1.5 ± 0.3	0 to 6,990	782 ± 980
2 to 3	165	4.6	2.5 ± 0.3	0 to 4,260	596 ± 782
3 to 4	181	5.0	3.5 ± 0.3	0 to 3,720	501 ± 525
>4	1,649	45.9	9.0 ± 3.6	0 to 4,410	239 ± 465
All Dry Season Days	3,591	100.0	4.5 ± 4.8	0 to 15,700	1,366 ± 2,201

Benthic communities are not only indicators of a salinity gradient, but are part of the food chain for many mobile aquatic species. Providing sufficient inflows to the CRE promotes spatial salinity gradients that are favorable for a wide range of benthic and water column communities. Reduced dry season freshwater inflows can cause freshwater and low salinity species and habitats in the upper CRE to be lost or reduced in size as these habitats are destroyed or relocated upstream (Chamberlain and Doering 1998a). Maintaining low salinity habitat is integral for at least part of the life cycle of mobile species such as *Callinectes sapidus* (blue crab), *Carcharhinus leucas* (bull shark), and *Pristis pectinata* (smalltooth sawfish; Hunt and Doering 2013) and many other species in the CRE (Stevens et al. 2010).

Component Study 7: Relationships between Salinity and the Survival of *Vallisneria americana* in the CRE

Christopher Buzzelli, Peter Doering, Zhiqiang Chen, and Yongshan Wan

Abstract

Vallisneria americana is sensitive to increased salinity in many estuaries, including the CRE. Much of the *Vallisneria* observed from 1993 to 1999 in the CRE has been lost since droughts in 2001 and 2007–2008. This study examined relationships between *Vallisneria* and salinity through change-point analysis, assessment of long-term patterns of abundance, and exploration of the effects of salinity exposure time. Change-point analysis revealed salinity thresholds of 4, 9, and 15. Dry season average daily salinity was ~5 and rarely exceeded 10 when *Vallisneria* was abundant from 1993 to 1999. Indicator inflows (Q_I) ranging from 0 to 3,160 cfs and averaging 545 ± 774 cfs were associated with dry season salinity values of 9 to 10 (n = 63) at the Ft. Myers station from 1993 to 1999. In contrast, *Vallisneria* was virtually absent from 2007 to 2013 as dry season average daily salinity exceeded 10. Negative changes in shoot density can be rapid as ~50 to 60% of the aboveground material was lost if salinity was > 10 for two to three weeks. These results highlight the effects of both the magnitude and duration of environmental conditions that can inhibit *Vallisneria* survival in the CRE.

Introduction

Vallisneria is a freshwater species of SAV commonly found in many lakes, rivers, and upper reaches of estuaries (Kraemer et al. 1999, Bortone and Turpin 2000, McFarland 2006). *Vallisneria* is dioecious, perennial, and capable of extensive clonal growth through the formation of belowground stolons (Lovett-Doust and LaPorte 1991). Northern populations overwinter as a dormant winter bud buried in the sediments (Titus and Hoover 1991). In South Florida, populations do not completely die back in winter as plants actively grow year round (Dawes and Lawrence 1989, Doering et al. 1999).

Vallisneria habitats are ecologically and economic important components in many estuaries (Wigand et al. 2000, Rozas and Minello 2006, Hauxwell et al. 2007). However, the survival of *Vallisneria* in estuaries can be modulated by interactions among salinity intolerance, submarine light limitation, and grazing by herbivores (Kraemer et al. 1999, Hauxwell et al. 2004, Dobberfuhl 2007, Moore et al. 2010). In particular, there have been many laboratory experiments to evaluate the responses of *Vallisneria* to altered salinity (**Table A-21**). Bourn (1932, 1943) reported that growth stopped at 8.4, while Boustany et al. (2010) found limited growth at 8.0. Haller (1974) reported growth at 10.0 but death at 13.3. While growth was minimal or zero when salinities ranged from 10.0 to 15.0, values > 15.0 caused mortality (Haller 1974, Doering et al. 2001, 2002, French and Moore 2003, Frazier et al. 2006, Boustany et al. 2010, Lauer et al. 2011). It is widely accepted that salinity > 10.0 can be damaging to the survival of *Vallisneria*.

Table A-21. Summary of *Vallisneria* salinity tolerances from a variety of studies in different locations.

REFERENCE	LOCATION	CONDITIONS	RESPONSE
		PLANTS	
Bourn 1932, 1943	Back Bay, VA	Static, acute 2-month exposure, outdoors, 11 salinity treatments	Growth stopped at a salinity of 8.4 in both winter and summer.
Haller 1974	Fort Lauderdale, FL	Static, acute 4-week exposure in greenhouse, 6 salinity treatments	Growth lower at salinities of 6.66 and 10 than at 0.17 and 3.33. Death at salinities of 13.32 and 16.65.
Twilley and Barko 1990	Potomac River, VA	Static, 5-week exposure outdoors, slowly raise salinity to treatment levels, 5 salinity (maximum 12) and 2 light treatments	No effect on growth at salinities of 0 to 12 regardless of light.
Doering et al. 1999	CRE, FL	Flow through mesocosms, 6-week exposure, artificial light, indoors, slowly raise salinity; 5 salinity treatments (maximum 15)	Growth declined with increasing salinity, nil or very slow at a salinity of 15.
Doering et al. 2002	CRE, FL	Flow through mesocosms, 5–6-week exposures, artificial light, indoors, slowly raise salinity; 10 salinity treatments (maximum 30)	Growth low or ceased at salinities of 10 and 15, mortality at salinities > 15.
French and Moore 2003	Maryland	Static, outdoor mesocosms exposure 7-month growing season, 4 salinity treatments (maximum 15), 3 light levels	Growth minimal at salinities of 10 and 15.
Boustany et al. 2010	St. Johns River, FL	Static, greenhouse, 10-week exposure, 10-week recovery, 3 salinity treatments (maximum 18), 3 light levels	Survived a salinity of 8, but growth was limited. Aboveground biomass perished after 10 weeks at a salinity of 18, 20% of these plants recovered after 10 weeks.
		DURATION	
Doering et al. 2001	CRE, FL	Flow through mesocosms, 0- to 70-day exposure to 18, 30-day recovery, artificial light, indoors, slowly raise salinity	Declines in blades and shoots observed after 5-day exposure. Statistically significant declines at 20- to 70-day exposures. Viable plants after 70 days.
Frazier et al. 2006	Kings Bay, Florida	Static, acute, 4 salinity treatments (maximum 25), 3 durations of exposure, 28-day recovery	100% mortality at a salinity of 25 after 1-, 2- , or 7-day exposure. 75% mortality at a salinity of 15 after a 7-day exposure. Exposure to a salinity of 5 had no effect on growth.
		FLOWERING	
French and Moore 2003	Maryland	See French and Moore 2003 above	No flowering at salinities of 10 or 15 regardless of light level.
Doering et al. unpublished 1999	CRE, FL	See Doering et al. 1999 above	Female structures at salinities of 0 and 3. Male structures at salinities of 0, 3, and 9. Neither structures at salinities of 12 or 15.
		SEEDS	
Nosach 2007	CRE, FL	Petri dishes, laboratory incubator, 3 temperature, 2 light, and 4 salinity (maximum 15) treatments	Seeds germinated at all salinities although rate declined as salinity increased. Temperature had the greatest effect with highest germination at 30 °C.
Jarvis and Moore 2008	Tidal tributary of the Potomac River, MD	Field characterization and laboratory experiments: (A) Salinity at 4 levels 1 to 15 in petri dishes; (B) temperature at 4 levels 13 to 29 ºC in petri dishes; (C) dark and light for oxygenated and hypoxic in 250 milliliter serum bottles; and (D) 4 treatments of varying sediment composition and 6 burial depths	Increased salinity had significant negative effect on germination with the threshold between salinities of 5 and 10. Seed viability was maintained at salinity > 10. Temperature exhibited a strong influence on germination with the highest germination occurring at > 22 °C. Oxygenation enhanced germination while light and burial depth (0.2 to 10 centimeter) had no effect.

Salinity also influences flowering and seed production in the life history of estuarine *Vallisneria* populations. French and Moore (2003) noted that flowering did not occur in salinity treatments of 10 and 15. Although the data were not included in Doering et al. (1999), they observed female flowers at 0 and 3, but not at 9 or above. Male flowers occurred at salinity values of 0, 3, and 9 but not when salinity was 12 or 15. Nosach (2007) examined the effects of temperature, light, and salinity on germination of *Vallisneria* seeds. Although seeds germinated across all salinities in this study (0 to 15), the best conditions for seed germination occurred at a temperature of 30 degrees Celsius (°C) and salinities < 5. Jarvis and Moore (2008) found that *Vallisneria* germination occurred best at temperatures > 22 °C and was significantly greater in salinity treatments of < 1 and 5 compared to the 10 and 15 treatments. Non-germinated seeds provide a pathway for revegetation by remaining viable throughout most environmental conditions.

The growing season for *Vallisneria* in the CRE in Southwest Florida lasts from March to September, with peak shoot density occurring in June or July (Bortone and Turpin 2000). Shoot density begins to decline in late summer as the production of male and female flowers is greatest in September or October. Blade length increases from March to September or October, sometimes to over a meter, and declines into the winter. Overwintering rosettes have short blades, 10 centimeters or less in length (Bortone and Turpin 2000).

Historically, there was abundant *Vallisneria* habitat in the upper CRE (Kraemer et al. 1999, Bortone and Turpin 2000, Doering et al. 2002, Bartleson et al. 2014). Published qualitative observations supported the presence of *Vallisneria* in the early 1960s (Gunter and Hall 1962, Phillips and Springer 1960). *Vallisneria* was present in the CRE from the mid-1980s until quantitative monitoring began in January 1998 (Bortone and Turpin 2000). Hoffacker (1994) conducted a visual census from July to October 1993 characterizing coverage as dense, moderate, or scattered. *Vallisneria* coverage was dense in the upper estuary between the Railroad Trestle near Beautiful Island and the Edison Bridge at Fort Myers (**Figure A-39**). The maximum downstream extent (Whiskey Creek) was documented in the Hoffaker map. When considered along with quantitative monitoring, it appears that there were dense beds of *Vallisneria* in the upper CRE from 1993 to 1999.

The management of freshwater inflow through the Franklin Lock and Dam at the head of the CRE (S-79; **Figure A-40**) is an important influence on circulation and transport in the CRE. Reduced freshwater inflow during the dry season (November–April) permits upstream encroachment of salt water (Wan et al. 2013, Buzzelli et al. 2014a). Superimposed on intraannual variations and water management are droughts such as the one in 2000–2001 when increased salinity led to widespread loss of *Vallisneria*. Rainfall for the CRE MFL Watershed (**Figure A-2A**) averages 51.1 inches annually. In 2001, the rainfall was only 35.8 inches, which was representative of a 1-in-25 year drought event. Another drought event occurred in 2007 that was equivalent to a 1-in-10 year drought. Additionally, for many years since 2000, dry season rainfall has been well below normal. As a result of multiple drought events and deficits in dry season rainfall, freshwater inflows in the CRE have been reduced.

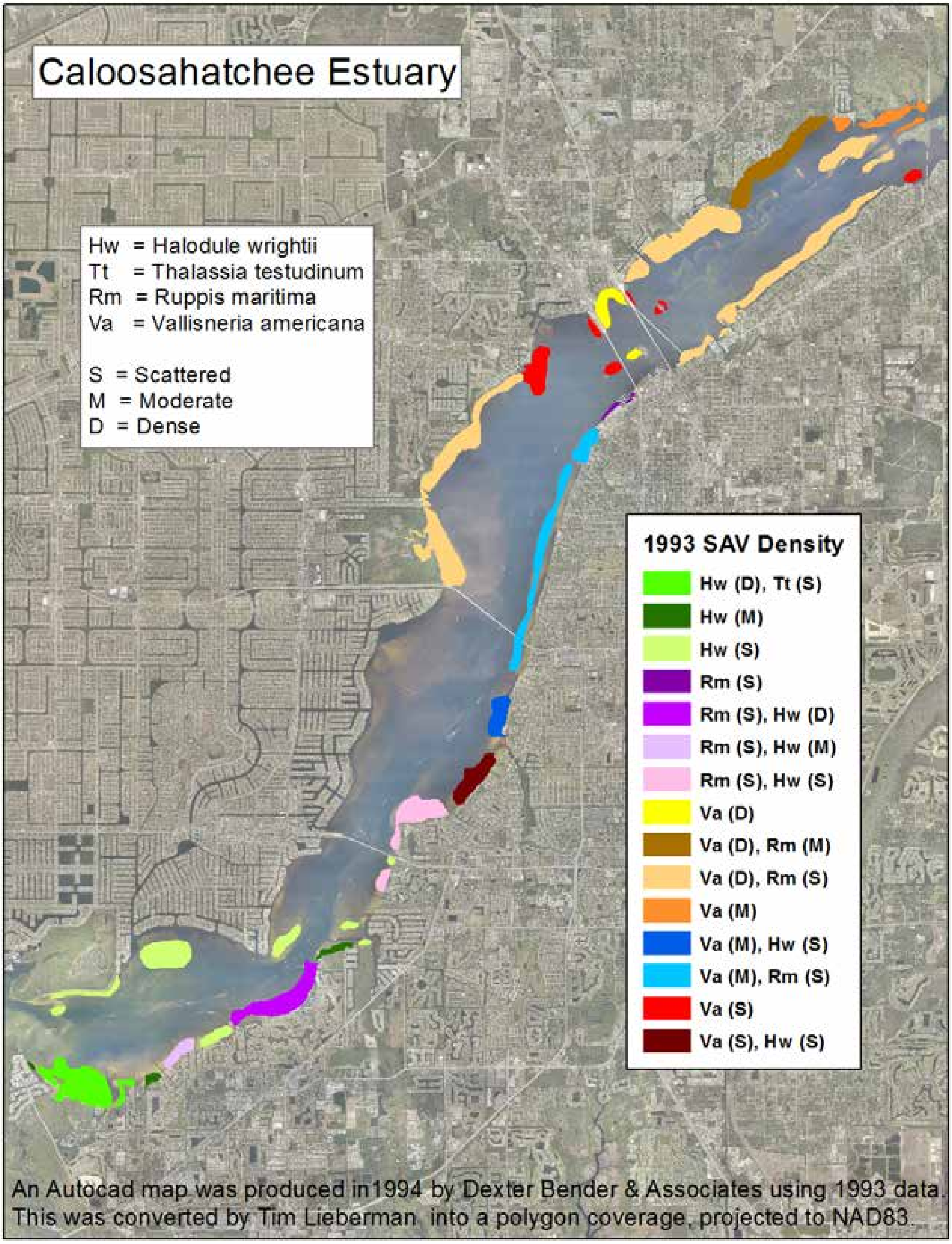


Figure A-39. 1993 map of SAV habitat density in the CRE from Hoffaker (1994).

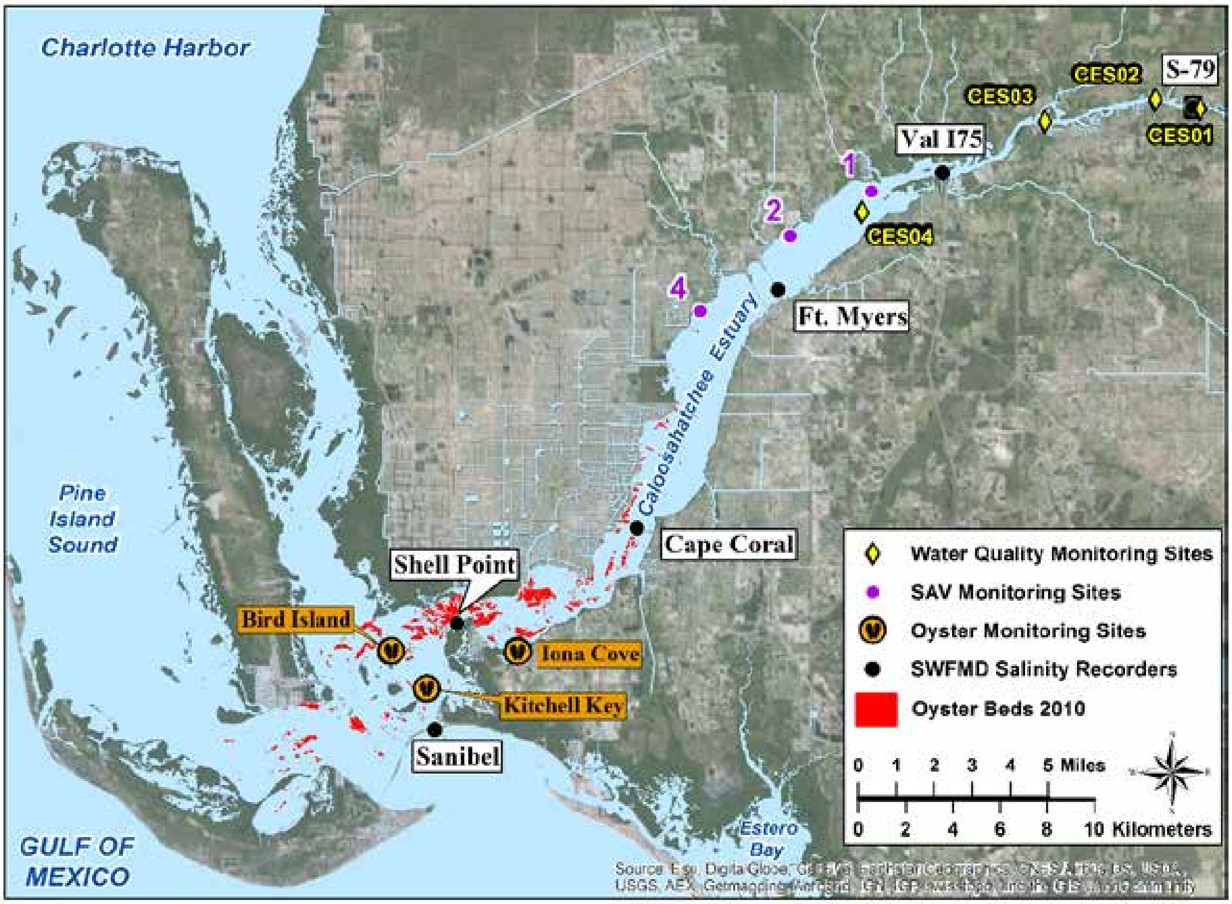


Figure A-40. Location map for the CRE including the S-79 water control structure, water quality monitoring sites, SAV monitoring sites (upper CRE), and the location of continuous salinity recorders.

Based on accumulated knowledge, this study assumed that salinity is the dominant driver for *Vallisneria* survival. This phenomenon was explored through local observations and data to assess survival of *Vallisneria* with fluctuating salinity using three separate approaches. The first was a statistical approach that applied Bayesian change-point analysis to determine the critical salinity values for *Vallisneria* (Beckage et al. 2007). This method uses piecewise regression to identify abrupt changes in sequential data (e.g. time series). The second was an assessment of long-term patterns of *Vallisneria* shoot densities and salinity. This approach provided an historical perspective that could help explain the present status of the resource. The relationship between the duration of super critical salinity and the proportional mortality of *Vallisneria* shoots was examined in the third approach.

Methods

Vallisneria Monitoring in the CRE

Quantitative monitoring of *Vallisneria* started in 1998 at Sites 1 through 4 (**Figure A-40**). Researchers established paired, perpendicular 100-m transects at each site. On each sampling date, the number of blades, shoots, and flowers were counted in five separate, random 0.1-m^2 quadrats along each transect (n = 10 = 5 quadrats x 2 transects; Bortone and Turpin 2000; Doering et al. 2002). Blade length and width were also determined in each quadrat. Field monitoring methods were changed in 2008 to a gridded presence/absence method where the number of cells containing shoots within a 1-m^2 quadrat was counted at multiple, randomly distributed sites. Because Site 3 was discontinued in 2003, there are three sites (1, 2, and 4) where shoot densities were monitored at approximately monthly intervals from 1998 to 2007. Data from Sites 1 and 2 were used in this study. Site 4 was omitted because *Vallisneria* presence was extremely variable at this most downstream station.

Salinity Monitoring in the CRE

Since 1992, SFWMD has monitored salinity at several locations in the CRE at 15-minute intervals (**Figure A-40**). Salinity is determined at two depths (20 and 80% of depth relative to mean sea level) using in situ data recorders. Daily average surface salinity recorded at the Ft. Myers station from May 1, 1992, to April 30, 2014, was obtained from DBHYDRO (my.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu). Missing daily salinity values (1,058 of 8,035 days) were estimated using an autoregressive model (Qiu and Wan 2013).

Data Analyses

Both salinity and *Vallisneria* shoot count data were expressed as a time series of water years. A water year spans May 1 to April 30 to include both wet (May–October) and dry (November–April) seasons representative of the subtropical climate of South Florida. There were a few different approaches to assess *Vallisneria*-salinity relationships.

First, salinity thresholds were quantified by applying Bayesian change-point analyses to the merged salinity-*Vallisneria* data (Qian et al. 2004, Ruggieri 2012). Change-point analyses successively split the data into two groups. At each split, the statistical properties (e.g. posterior means) of the two groups are evaluated to determine the likelihood (probability) that each group is statistically similar unto itself and at the same time statistically distinct from the opposing group. The most probable change point was considered to represent a change point threshold of salinity with uncertainty quantified by constructing a high density credible interval around this threshold. The Bayesian change point package in "R" was used (cran.r-project.org/web/packages/bcp/; Erdman and Emerson 2007). Shoot density data were log transformed to normalize the distribution. In addition, shoot density data were binned based on integer salinity values from 1 to the maximum salinity observed. The procedure results in posterior means and a probability distribution over salinity groups. Change points of salinity were chosen as salinities where there was maximum probability of difference among adjacent data groups at each split.

Second, historical differences in indicators of *Vallisneria* abundance and salinity were assessed to better understand the conditions that either promote or inhibit *Vallisneria*. This was accomplished by defining two equivalent time periods each containing seven wet and six dry seasons for analysis of salinity patterns. The two periods were May 1, 1993–October 31, 1999 (WY1994 to wet season of WY2000), and, May 1, 2007–October 31, 2013 (WY2008 to wet season WY2014). Salinity patterns during these time periods were qualitatively compared to shoot densities from Site 2. Data from the first period (WY1993–WY1999) were queried to extract the dry season days where salinity at the Ft. Myers station was 9 to 10. These inflows were assumed to be below the desirable limit to maintain favorable salinity conditions.

Finally, the effects of exposure time on the survival of *Vallisneria* were examined using the observed shoot densities at Sites 1 and 2 and the Ft. Myers salinity record. The 30-day moving average salinity was calculated. Four time periods among the two sites were selected to assess decreases in shoot density with critical salinity values. Not all high salinity (30-day average salinity

> 10) events were included in the data set. Two episodes occurring between March and June 2002 were excluded because initial shoot density was too low (£ 11 shoots per square meter [m^{-2}]) to quantify a decline. An episode that occurred in 1999 also was not included. While plants did decline, the decline itself began well before salinity at Ft. Myers reached 10 and other factors either singly or in combination with salinity may have been responsible. For the remaining intervals, the shoot density on the first day was used as the initial condition. The number of days where the 30-day moving average salinity exceeded 10 (x) was paired with the percent of shoots remaining relative to the initial conditions (y) and modeled using a negative exponential curve.

Results

Salinity at the Ft. Myers station varied on seasonal, annual, and multiannual time scales (**Figure A-41A**). It was greatest in the dry season peaking at ~26 and 27 in 2001, 2007, and 2008. Values were generally lowest from 2003 to 2006. Average shoot densities ranged from 0 to 370 and 0 to 1,200 shoots per m^{-2} at Sites 1 and 2 (**Figure A-41B**). Shoots were abundant from 1998 to 2000 with densities at Site 2 much greater than those observed at Site 1. Shoot densities were much reduced and similar between the two sites in 2000 before dropping to near zero from 2001 to 2004. Density increased slightly to 0 to 200 shoots per m^2 from 2004 to 2006 before again falling to zero in 2007.

The Bayesian change-point analysis resulted in clear salinity thresholds of 4, 9, and 15 (**Figure A-42**). These values reinforce previous findings where salinity values that were ³ 5 impaired growth, those ³ 10 stopped growth, and salinity values ³ 15 caused mortality. The first threshold (4) was associated with the highest shoot densities. The most pronounced change point of salinity was around 9 (posterior probability of 86%) with the 95% credibility limit from 8 to 10. Salinity values > 9 were associated with decreased densities from 200 to 100 shoots per m^2. The inflection point around a salinity of 15 had a probability of 0.6 and a 95% credibility limit of 14 to 16. Salinity values > 15 were associated with decreased densities to < 40 shoots per m^2.

Anecdotal, observational, and quantitative information indicated large differences in *Vallisneria* distribution and density between the two time periods (WY1993–WY1999 and WY2007–WY2013; **Figure A-42**). The Hoffaker map (1994; **Figure A-39**) revealed extensive *Vallisneria* habitat throughout the upper half of the CRE. Personal observations by SFWMD staff (P. Doering and R. Chamberlain) confirmed dense beds of *Vallisneria* from the WY1995–WY1997 period. Shoot densities derived from in situ counts ranged from 200 to 900 shoots per m^2 from WY1998 to WY2000 across the habitat area. Both the distribution and abundance declined through 2001 reaching ~0.0 from 2002 to 2003. There were small observable increases in shoot density from WY2004 to WY2007. However, monitoring conducted since WY2008 indicated that *Vallisneria* has been mostly absent except for a minor appearance in WY2011.

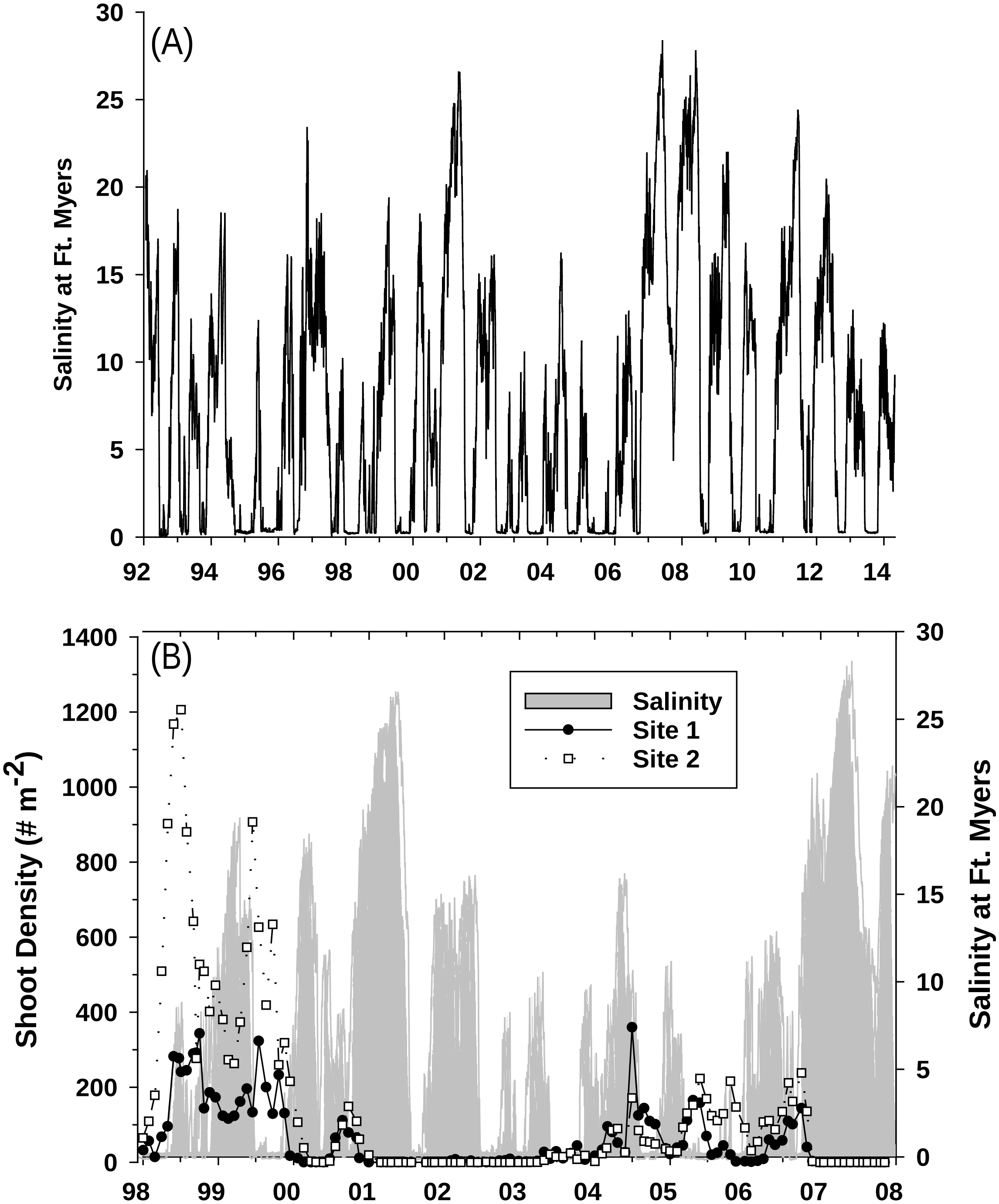


Figure A-41. (A) Time series of daily average surface water salinity at the Ft. Myers station from January 1992 to April 2014. (B) Time series of average *Vallisneria* shoot densities (# m^{-2}) at Sites 1 (filled circle) and 2 (open square) in the CRE from 1998 to 2007. (Note: Average daily surface salinity at Ft. Myers is shown as the grey filled time series, right axis.)

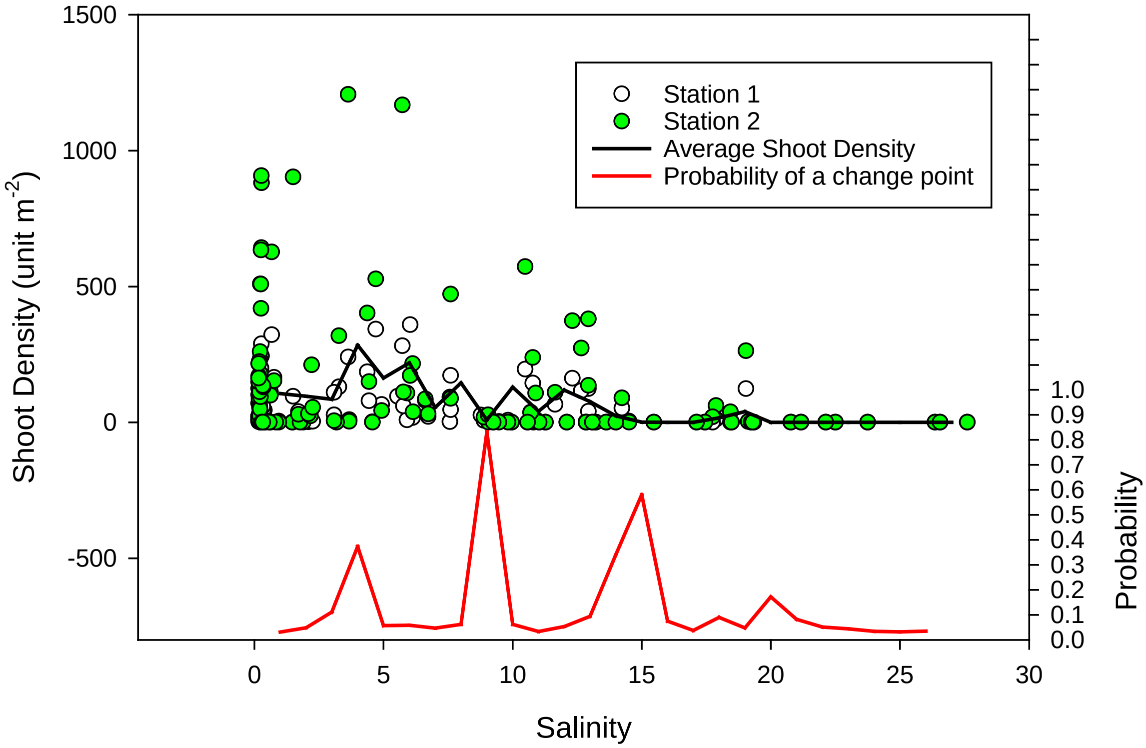


Figure A-42. Combination plot showing *Vallisneria* shoot densities (unit per m^2 [unit m^{-2}]; left axis) from monitoring Sites 1 and 2 as a function of the 30-day moving average salinity at Ft. Myers. (Note: The red line depicts the probabilities of break points in the relationship between shoot density and salinity.)

Daily surface salinity at the Ft. Myers station over the entire POR (May 1, 1993–April 30, 2014) averaged 7.17 ± 7.09 (n = 8,035). During the period when *Vallisneria* beds were likely extensive and dense (WY1993–WY1999), daily salinity averaged 5.4 ± 5.4 (n = 2,375; **Table A-22**).

Table A-22. Descriptive statistics for salinity values at the Ft. Myers station. (Notes: Two equal subsets of data were extracted from the long-term [1992–2014] time series. Period 1 was from May 1, 1993, to October 31, 1999. Period 2 was from May 1, 2007, to October 31, 2013.)

Salinity Statistic	Period 1	Period 2
Number	2,375	2,376
Range	0.03–23.4	0.15–28.3
Average + Standard Deviation	5.4 ± 5.4	10.0 ± 8.0
Median	3.6	10.3

In contrast, salinity during the period when *Vallisneria* was virtually absent (WY2007–WY2013) averaged 10.0 ± 8.0 (n = 2,376). One-way ANOVA showed these averages to be significantly different ($p < 0.001$). In general, *Vallisneria* requires salinities below 10 for a sustainable population (French and Moore 2003). Average seasonal salinity exceeded this value only once during the first period when *Vallisneria* was abundant (dry season 1997; **Figure A-43**).

During the more recent period when *Vallisneria* was sparse or absent, average salinity exceeded this threshold in five of six dry seasons and three of six wet seasons. Freshwater inflows ranging and averaging 0 to 3,160 and 545 ± 774, respectively, were associated with dry season salinity values of 9 to 10 (n = 63) at the Ft. Myers station in Period 1 when *Vallisneria* was abundant (WY1993–WY1999).

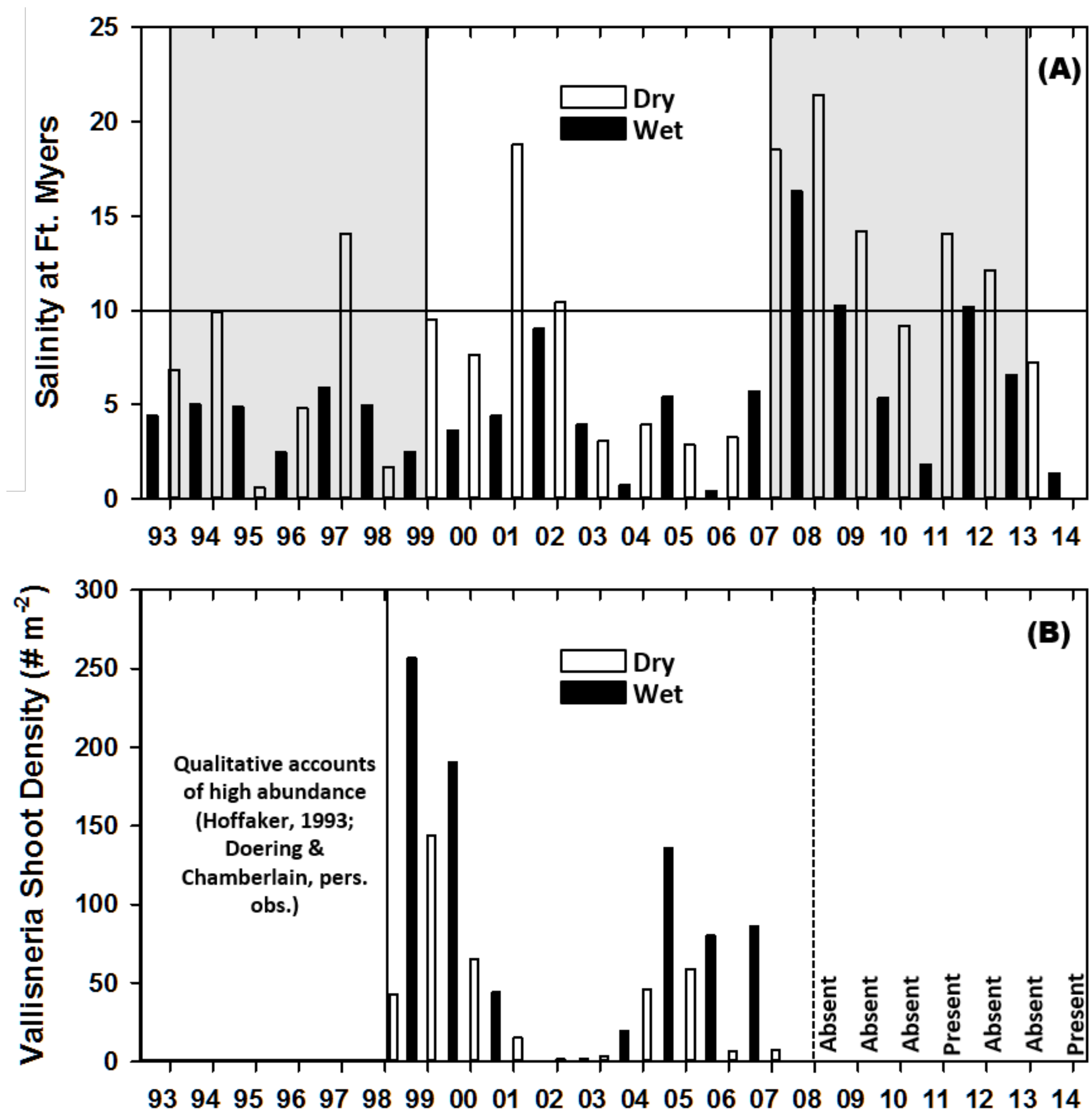


Figure A-43. (A) Time series of average seasonal salinity at the Ft. Myers station from 1993 to 2014. (B) Time series of average seasonal shoot density from 1998 to 2007. (Notes: Data before this period were qualitative. Monitoring methods changed to detect presence versus absence since 2008. In A, the shaded areas mark two separate seven-year periods [1993–1999 and 2007–2014].)

Vallisneria shoot density decreased precipitously with increased duration of 30-day average salinity values in excess of 10 at the Ft. Myers station (**Table A-23** and **Figure A-44**). The negative exponential relationship suggests that a 50% reduction in plant density would occur after 14 days, an 85% reduction after 42 days, and a 95% reduction after 63 days. Examination of the upper confidence limit on the mean prediction of the equation revealed that significant mortality occurred after 4 days (95% confidence interval no longer overlaps 100% remaining).

Table A-23. Time periods and data used to calculate percent change in *Vallisneria* shoot densities relative to salinity criteria at the Ft. Myers station. (Note: See text and **Figure A-44** for details and results.)

Station 1					
Start	**End**	**Initial Shoots**	**Days**	**% Remaining**	**Comment**
2/27/2000	3/16/2000	10.5	19	0	Not used
11/18/2000	3/26/2001	79	11	83	
			24	17	
			70	0	
5/20/2004	6/23/2004	52	36	50.7	
11/12/2006	1/24/2007	143.9	10	28	
			37	1.7	
Station 2					
Start	**End**	**Initial Shoots**	**Days**	**% Remaining**	**Comment**
2/27/2000	4/20/2000	107	19	36	
			34	1.6	
11/18/2000	3/26/2001	149	11	74	
			24	56	
			70	18	
			127	0	
5/20/2004	6/23/2000	90	36	29.78	
11/12/2006	1/24/2007	238.3	10	56.95	
			37	1.0	

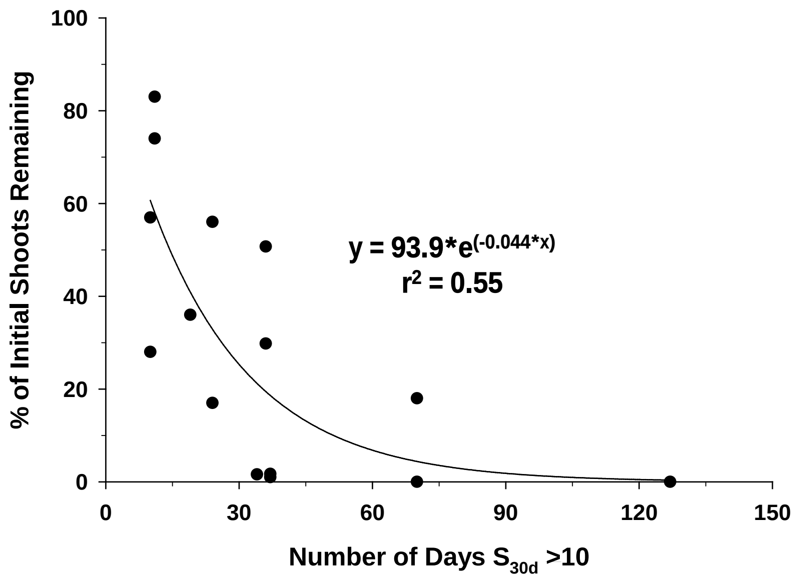


Figure A-44. Proportional mortality plot showing the number of days where salinity at the Ft. Myers station was $S_{30d} \geq 10$ versus the percent of initial shoots remaining. (Note: See text and **Table A-23** for details of analysis.)

Discussion

This study represents an important step towards an improved understanding of the survival of *Vallisneria americana* in the CRE in Southwest Florida. This understanding builds upon a foundation of original accounts, local surveys, quantitative monitoring, mesocosm experiments, statistical analyses, and simulation modeling (Hoffaker 1994, Doering et al. 1999, Bortone and Turpin 2000, Doering et al. 2002, Bartleson et al. 2014, Buzzelli et al. 2015b). While estuarine *Vallisneria* is sensitive to multiple environmental factors (e.g. light, grazing, and temperature), it appears that the dominant driver is salinity (French and Moore 2003, Dobberfuhl 2007, Boustany et al. 2010, Lauer et al. 2011).

Salinity is a conservative property of estuaries that, while uninfluenced by biogeochemical processes, varies over many time scales through complex hydrodynamic processes. These processes integrate rainfall, surface inflows, groundwater discharge, wind events, and tidal exchanges to establish salinity conditions (Zheng and Weisberg 2004) and modulate biological processes (Jassby et al. 1995, Livingston et al. 1997, Whitfield et al. 2012). Thus, estuaries are very sensitive to anthropogenic changes in freshwater inflow (Alber 2002). Physical alterations such as dredging and dams change natural inflows, impact mixing with the coastal ocean, and dramatically affect salinity and water quality in the estuary (Day et al. 1989, Zhu et al. 2015). Discharge, salinity gradients, biogeochemical properties, and biological attributes of the CRE are greatly influenced by a combination of subtropical climatic variability and landscape-scale water management (Tolley et al. 2005, Volety et al. 2009, Buzzelli et al. 2013d, Wan et al. 2013).

The location of particular isohalines in estuaries can be used as an indicator of ecological conditions (Jassby et al. 1995). In the case of the CRE, a salinity of 10 at the Ft. Myers station has been established as a benchmark for water management (Balci and Bertolotti 2012). The long-term salinity record at Ft. Myers provides an excellent indication of the environmental suitability for *Vallisneria* in the upper CRE. Increasing salinity thresholds of 4 to 5, 8 to10, and > 15 serve to slow growth, inhibit survival, and cause mortality in estuarine populations of *Vallisneria*, respectively (Bourn 1932, 1943, Haller 1974, Doering et al. 2001, 2002, French and Moore 2003, Frazier et al. 2006; Boustany et al. 2010, Lauer et al. 2011).

This study demonstrated that differences in salinity between two time periods (1993–1999 and 2007–2013) may have contributed to observed differences in density and spatial extent of *Vallisneria* in the upper CRE. During the initial period when *Vallisneria* beds were dense and widespread, salinity was ~5 and seasonally averaged salinity rarely exceeded 10 for a sustainable population. There was a 40% reduction in freshwater inflow to the upstream estuary during the second seven-year period. Reduced freshwater inflow is an important driver leading to increased salinity in the CRE. When *Vallisneria* was virtually absent in the second period, salinity was ~10 with multiple wet and dry seasonal exceedances of this threshold.

It is not surprising that the *Vallisneria* habitat in the CRE has trouble recovering from repeated, severe drought-induced stress in 2001 and 2007–2008. Salinity in the CRE has been much higher since 2007 as compared to the last known period of *Vallisneria* abundance (WY1993–WY1999). Additionally, approximately half of the standing stock could be lost if salinity at the Ft. Myers station is greater than 10 for 14 consecutive days. Loss of mature shoots inhibits the potential to reestablish viable habitat through vegetative and reproductive growth. The cumulative impacts of anthropogenic changes, increased salinity, decreased shoot density, and shrunken habitat extent have created circumstances that greatly inhibit the recovery of *Vallisneria* habitat in the CRE.

Component Study 8: Development and Application of a Simulation Model for *Vallisneria americana* in the CRE

Christopher Buzzelli, Peter Doering, Yongshan Wan, and Teresa Coley

Abstract

Monitoring of *Vallisneria americana* densities in the upper CRE from 1998 to 2007 was accompanied by mesocosm experiments to determine relationships between salinity and growth. This study built upon these efforts by developing a simulation model to examine the effects of temperature, salinity, and light on *Vallisneria* survival and biomass in the upper CRE from 1998 to 2014. The effects of salinity on *Vallisneria* mortality were explored using an eight-year experimental model based on favorable conditions from 1998 to 1999. Using the experimental model, the dry season salinity was systematically increased in 5% increments until the net annual biomass accumulation of *Vallisneria* was negative. A five-fold increase in grazing was required to stabilize model biomass under optimal conditions. A 55% salinity increase to 12 promoted shoot mortality in the experimental model. Annual inflow-salinity relationships for the Ft. Myers station were used to estimate that dry season inflows ranging from 15.2 to 629.0 cfs and averaging 342 ± 180 cfs were associated with a salinity of 12 at Ft. Myers. Model results suggested that an estimated 85.4 and 86.7% of the shoots were lost in the dry seasons of 2001 and 2007, respectively.

Introduction

Vallisneria is a freshwater species of SAV commonly found in many lakes, rivers, and upper reaches of estuaries (Bortone and Turpin 2000, McFarland 2006). *Vallisneria* habitat in estuaries is desirable since it supports a variety of ecologically and commercially important fauna (Wigand et al. 2000, Hauxwell et al. 2004, Rozas and Minello 2006). Because it is a freshwater organism that can extend into oligohaline estuarine areas, *Vallisneria* is very responsive to fluctuations in salinity (Doering et al. 2002, Boustany et al. 2010).

There have been many laboratory experiments to evaluate the responses of *Vallisneria* to altered salinity. Salinity values in excess of 8 to 15 can be stressful and result in net mortality depending upon exposure time (Doering et al. 1999, Doering et al. 2001, French and Moore 2003, Boustany et al. 2010, Lauer et al. 2011). Bourn (1932, 1943) reported that growth stopped at 8.4, while Boustany et al (2010) found limited growth at 8.0. Haller (1974) reported growth at 10.0 but death at 13.3. While growth was minimal or zero when salinities ranged from 10.0 to 15.0, values > 15.0 caused mortality in several studies (Haller 1974, Doering et al. 2001, French and Moore 2003, Frazier et al. 2006, Boustany et al. 2010, Lauer et al. 2011). It is generally accepted that salinity > 10.0 is detrimental to *Vallisneria*.

Water clarity is a complicating factor that can affect the survival and growth of *Vallisneria* in estuaries. Submarine light penetration in the upper part of estuaries is affected by colored dissolved organic matter, which is directly proportional to freshwater inflow (McPherson and Miller 1994, Bowers and Brett 2008, Buzzelli et al. 2014b). *Vallisneria* requires ~9 to 14% of surface irradiance with total light extinction coefficients of 3 to 4 per m being most favorable (French and Moore 2003, Dobberfuhl 2007, Boustany et al. 2010, Moore et al. 2010). The obvious implication is that the low salinity necessary for *Vallisneria* survival in oligohaline estuarine areas is usually accompanied by decreased light levels.

The growing season for *Vallisneria* in Southwest Florida lasts from March to September, with maximum shoot density and biomass occurring in July–August (Bortone and Turpin 2000). Published qualitative observations supported the presence of *Vallisneria* in the early 1960s (Gunter and Hall 1962, Phillips and Springer 1960) and the 1980s (Bortone and Turpin 2000). Hoffacker (1994) conducted a visual census from July to October 1993 that documented widespread coverage with variable density. The negative response of *Vallisneria* to increased salinity makes it an excellent ecological indicator for freshwater management (Doering et al. 2002). It provides a useful indicator because its sensitivity provides insight into environmental conditions that trigger problems at the habitat scale (Dale and Beyeler 2001).

The distribution and density of *Vallisneria* habitat is variable in the upper CRE in Southwest Florida (Kraemer et al. 1999, Bortone and Turpin 2000, Doering et al. 2002, Bartleson et al. 2014). The decreased availability of fresh water in the dry season (November–April) can lead to reduced freshwater inflow and the upstream encroachment of saline water (Wan et al. 2013, Buzzelli et al. 2014a). These attributes were particularly acute during droughts in 2001 and 2007–2008 when salinity increases in the upper CRE led to widespread loss of *Vallisneria*.

The goal of this study was to develop a simulation model for *Vallisneria* in the CRE (Buzzelli et al. 2012, 2014b). There has been much environmental monitoring since initial efforts to use *Vallisneria* as an indicator of freshwater inputs over a decade ago. These data provide an empirical foundation for ongoing management, and the creation of a mathematical model to forecast potential responses to proposed management actions. The objectives were to develop and test a simulation model of *Vallisneria* responses to environmental variables (temperature, salinity, and light) and evaluate the salinity and inflow conditions that support viable oligohaline (0–10) SAV habitat in the upper CRE.

Methods

Study Site

The CRE is bounded upstream by S-79 and extends ~42 km downstream to the mouth near the Sanibel Bridge (**Figure A-45**). The surface area of the CRE is 67.6 km^2 (6,764 hectares = 16,715 acres) with an average depth of 2.7 m (Buzzelli et al. 2013a). Average flushing time ranges from 5 to 60 days (Wan et al. 2013, Buzzelli et al. 2013d). A variety of physical, chemical, and biological variables are regularly monitored by SFWMD and other organizations. Discharge from S-79 has been recorded since 1966 and is reported here as the daily mean average inflow rate in cfs. Salinity has been monitored at multiple locations since the 1990s (S-79, Val I75, Ft. Myers, Cape Coral, Shell Point, and Sanibel; **Figure A-45**). The distribution and density of SAV have been determined at the upper stations (1, 2, and 4) since 1998 and in the lower estuary (5, 6, 7, and 8) every two months since 2004. This study focused on SAV Site 1 because of its upstream location near Beautiful Island and proximity to the Ft. Myers salinity monitoring location.

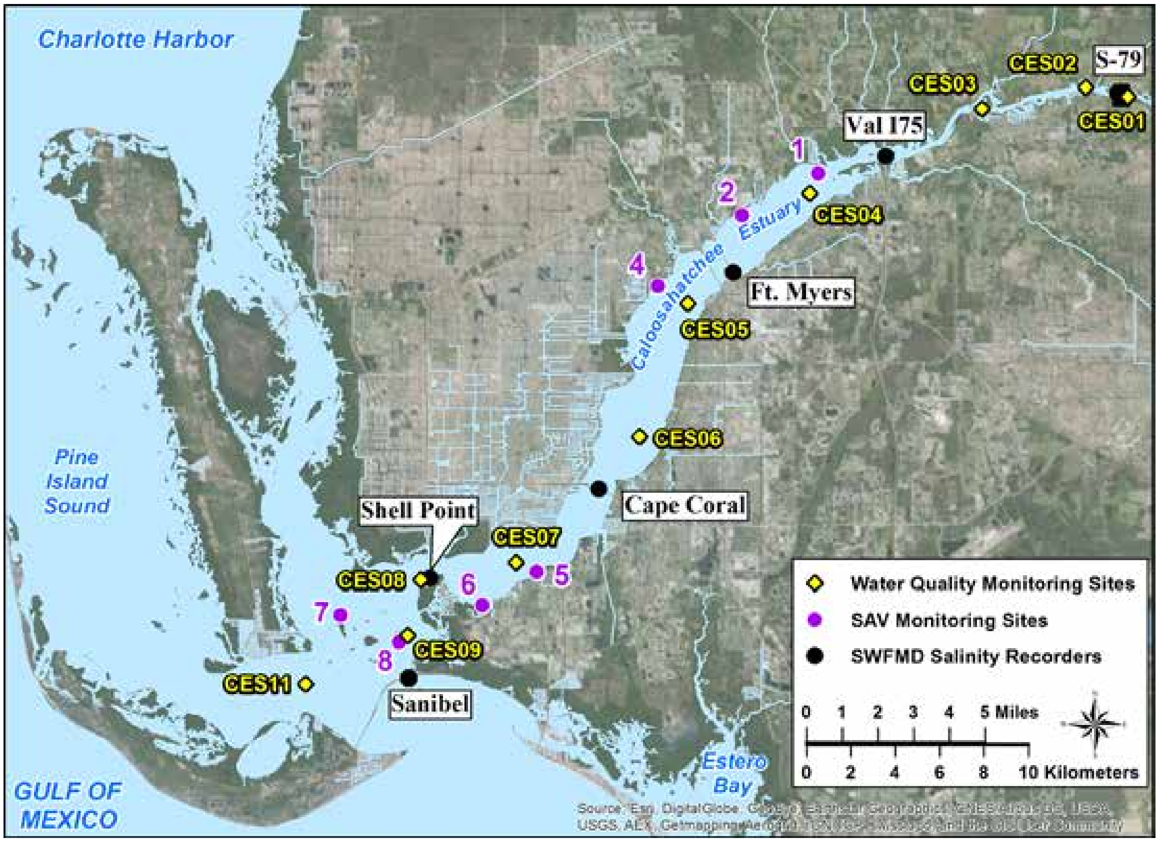


Figure A-45. Location map for the CRE including the S-79 water control structure, water quality monitoring sites, SAV monitoring sites, and the location of continuous salinity recorders.

Empirical Data

Daily average surface salinity recorded at the Ft. Myers station from May 1, 1992, to April 30, 2014, was obtained from the DBHYDRO, which is accessible from the following link: https://www.sfwmd.gov/science-data/dbhydro). Missing daily salinity values (1,058 of 8,035 days) were estimated using an autoregressive model (Qiu and Wan 2013).

Researchers established paired, perpendicular 100-m transects at the beginning of the SAV monitoring period for each site. On each sampling date the number of blades, shoots, and flowers were counted in five separate, random 0.1-m^2 quadrats along each transect (n = 10 = 5 quadrats x 2 transects; Bortone and Turpin 2000, Doering et al. 2002). Blade length and width were also determined in each quadrat. SAV shoot counts, length, width, and dry weight biomass were monitored approximately bimonthly at Site 1 from 1998 to 2007.

Both salinity and *Vallisneria* shoot count data were expressed as a time series of water years. Each water year includes wet (May–October) and dry (November–April) seasons representative of the subtropical climate of South Florida. Mesocosm experiments provided data used to generate a linear regression between shoot densities and aboveground biomass (Doering et al. 1999, 2001). This relationship was used to convert shoot densities (number per square meter [# m^{-2}]) observed at Site 1 to biomass (grams dry weight per square meter [gdw m^{-2}]) and generate a time series of shoot biomass from 1998 to 2007. This time series was used to calibrate model predictions of shoot biomass. The regression relationship also was used to convert predicted shoot biomass back to shoot density for various applications.

Model Boundaries

Vallisneria habitat near Beautiful Island in the upper CRE provided the spatial reference for the model (Doering et al. 2001). The model was developed to represent changes in biomass at Site 1 over an 18-year period from 1997 to 2014 (6,574 days or 216 months). The integration interval was 0.75 hours (0.03125 day; Buzzelli et al. 2012, 2014b). The first year of simulation time (1997) was used to stabilize the model and was not included in reporting and interpretation. The model output (1998–2014) was summed or averaged to depict daily, monthly, seasonal, and annual (calendar and water year) time scales.

Model Mathematical Structure

Water temperature (T_w), submarine light (I_z), and salinity (S) were the important environmental drivers for the *Vallisneria* model (**Figure A-46** and **Tables A-24** and **A-25**). A daily time series of T_w at the Ft. Myers station from 1998 to 2012 was derived from continuous monitoring (**Figure A-47A**). Missing temperature data were estimated using an interpolation method (Baldwin and Hunt 2014). Temperature influences both the photosynthesis-irradiance relationship (fT_{shoot}) and the effective rate of respiration (**Tables A-24** and **A-25**, and **Figure A-47B**).

Daily salinity at SAV monitoring Site 1 (S_{val1}) was predicted using a method derived through integrated hydrodynamic and time series modeling (**Figure A-48A**; Qiu and Wan 2013). The method combines empirically derived freshwater inflow through S-79, estimated freshwater input through combined tributaries and groundwater inflows from the downstream Tidal Basin, and daily salinity data observations from the I-75 Bridge in the upper CRE to generate a continuous time series of salinities at Site 1 (Qiu and Wan 2013). S_{val1} was used to influence rates of *Vallisneria* gross production and loss. A salinity range of 0 to 10 decreased and increased the model rates of gross production and mortality, respectively (**Figure A-48B**).

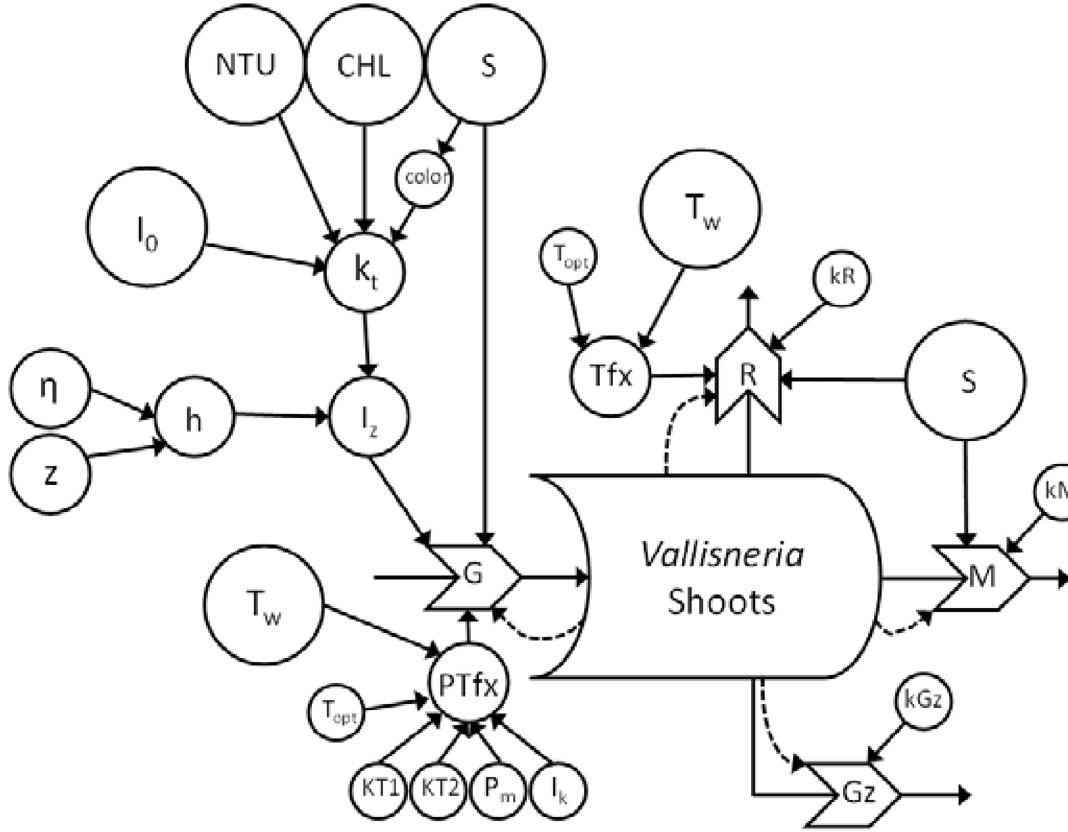


Figure A-46. Conceptual model for response of *Vallisneria* shoots to variable water temperature (T_w), irradiance at the bottom (I_z), and salinity (S). (Notes: See **Tables A-24** and **A-25** for model equations and coefficients, respectively. Surface irradiance [I_0], turbidity [NTU], chlorophyll *a* [CHL], and color were used to calculate I_z. S was used as a term to estimate color. Depth [h] was calculated using water level [η] and sediment elevation [z]. A suite of coefficients—optimum temperature [T_{opt}], *Vallisneria* constants for photosynthesis [KT1] and [KT2], maximum rate of photosynthesis [P_m], and the half-saturation irradiance value [I_k]—are combined with T_w and shoot biomass to calculate gross production [G]. Respiration [R] is influenced by a temperature effect [Tfx] and S. S also influences the rate of shoot mortality [M]. Loss due to grazing [Gz] is a function of the shoot biomass and the basal grazing rate [kGz].)

Table A-24. List of equations to simulate dynamics of *Vallisneria americana* shoot biomass. (Note: See Buzzelli et al. [2012, 2014b] for mathematical details.)

Description	Equations
(1) Photoperiod (P_{photo}; hrs)	$P_{photo} = 12 - 2 * \cos(\frac{2 * \pi * day}{365})$
(2) Surface irradiance (I_0; µmole m^{-2} s^{-1})	$I_0 = MAX[(I_{amp} * \cos(\frac{2 * \pi * (hour - 12)}{2 * P_{photo}})), 0.0]$
(3) M_2 water level (η; m)	$\eta = MSL + (AM2 * \cos(2 * \pi * (\frac{hour - PhM2}{TM2})$
(4) Water Depth (h; m)	$h = \eta - z$
(5) Light extinction coefficient (k_t; m^{-1})	$k_t = k_w + [k_{color}] + [a_{NTU} * NTU] + [a_{CHL} * CHL]$
(6) Light extinction color (k_{color}; m^{-1})	$k_{color} = a_{color} * e^{(-b_{color} * S)}$
(7) Light at bottom (I_z; µmole m^{-2} s^{-1})	$I_z = I_0 * e^{(-k_t * h)}$
(8) Percentage of surface light at bottom ($\%I_z$)	$\%I_z = (\frac{I_z}{I_0}) * 100$
(9) *Vallisneria* shoot (C_{shoot}; gC m^{-2})	$\frac{dC_{shoot}}{dt} = G_{shoot} + N_{shoot} - R_{shoot} - M_{shoot} - Gz_{Shoot}$
(10) *Vallisneria* shoot growth (G_{shoot})	$G_{shoot} = P_m * [\frac{I_z}{(I_k + I_z)}] * fS_{gross} * fT_{shoot} * [1 - (\frac{C_{shoot}}{C_{max}})] * C_{shoot}$
(11) *Vallisneria* photosynthesis T effect (Tfx_{shoot})	$fT_{shoot} = IF(T_w \leq T_{opt}) e^{-kT1 * (T - T_{opt})^2}$
	$fT_{shoot} = IF(T_w > T_{opt}) e^{-kT2 * (T_{opt} - T)^2}$
(12) *Vallisneria* new shoots (N_{shoot}; gC m^{-2} d^{-1})	$N_{shoot} = C_{shoot} * kN$
(13) *Vallisneria* shoot respiration (R_{shoot}; gC m^{-2} d^{-1})	$R_{shoot} = C_{shoot} * [kR * e^{KfB(T_w - T_{opt})}]$
(14) *Vallisneria* shoot mortality (M_{shoot}; gC m^{-2} d^{-1})	$M_{shoot} = C_{shoot} * kS_{loss} * fS_{loss}$
(15) *Vallisneria* shoot grazing (Gz_{shoot}; gC m^{-2} d^{-1})	$Gz_{shoot} = kGz * C_{shoot}^2$

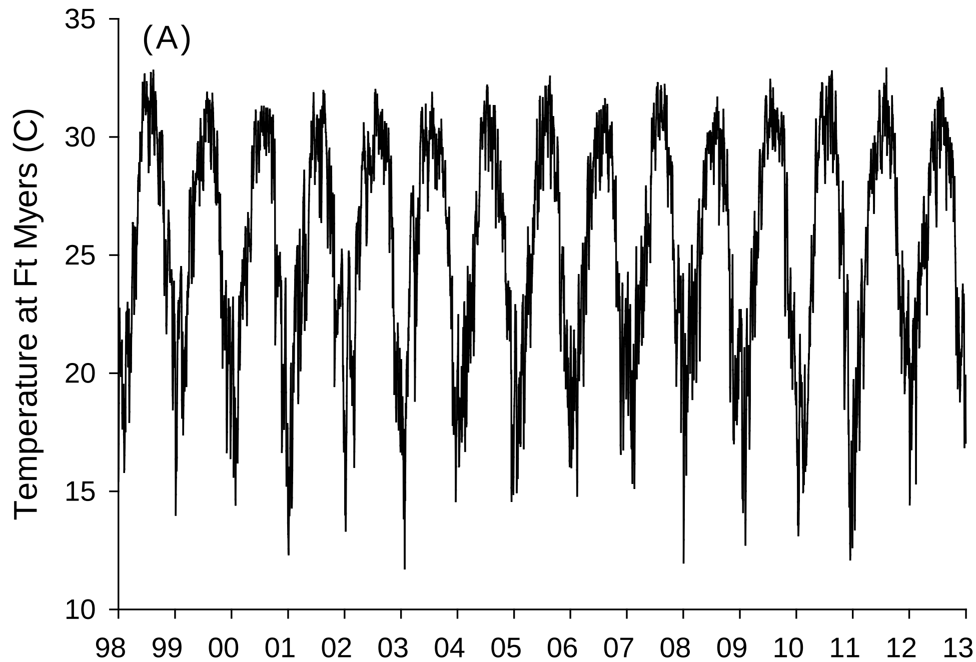
Key to units: µmole m^{-2} s^{-1} – micromoles per square meter per second; gC m^{-2} – grams shoots per square meter; gC m^{-2} d^{-1} – grams shoots per square meter per day; hrs – hours; m – meters; and m^{-1} – per meter.)

Table A-25. List of *Vallisneria* model coefficients.
(Note: See Buzzelli et al. [2012, 2014b] for mathematical details.)

Parameter	Value	Unit	Description	Source
I_{amp}	1000	µmole m^{-2} d^{-1}	Amplitude of surface irradiance	local data
MSL	0.0	m	Mean sea level	***
TM2	12.42	hours	Period of M2 tide	NOAA Ft. Myers
AM2	0.111	m	Amplitude of M2 tide	NOAA Ft. Myers
PhM2	1.43	radians	Phase angle of M2 tide	NOAA Ft. Myers
z	-0.75	m	Sediment elevation of habitat	USGS bathymetry data
k_w	0.15	m^{-1}	Attenuation due to water	Calculated from Gallegos 2001
a_{NTU}	0.062	NTU^{-1}	Attenuation factor for turbidity	McPherson and Miller 1987
a_{CHL}	0.058	m^3 mg^{-1}	Attenuation factor for chlorophyll *a*	McPherson and Miller 1987
a_{color}	2.89	m^{-1}	Constant for salinity-color relationship	McPherson and Miller 1987
b_{color}	0.096	m^{-1}	Constant for salinity-color relationship	McPherson and Miller 1987
T_{opt}	28	°C	Optimum temperature for rate processes	Bartleson et al. 2014
KtB	0.069	$°C^{-1}$	Rate constant for temperature effect	Buzzelli et al. 1999
P_m	0.02	d^{-1}	Vallisneria max photosynthetic rate	Blanch et al. 1998
I_k	56	µmole m^{-2} d^{-1}	Vallisneria light constant	Blanch et al. 1998
kT1	0.004	unitless	Vallisneria temperature constant for photosynthesis	Buzzelli et al. 1999
kT2	0.006	unitless	Vallisneria temperature constant for photosynthesis	Buzzelli et al. 1999
kN	0.01	unitless	Vallisneria source of new shoots	Calibration
kR	0.001	d^{-1}	Vallisneria shoot respiration rate	Calibration
kS_{los}	0.01	d^{-1}	Vallisneria loss rate with salinity	Calibration
kGz	0.0002	m^2 gdw^{-1}	Vallisneria shoot grazing rate	Calibration
C_{init}	15	gdw m^{-2}	Vallisneria initial shoot biomass	Calibration - CRE data
C_{max}	100	gdw m^{-2}	Vallisneria maximum shoot biomass	Calibration - CRE data

Key to units: °C – degrees Celsius; $°C^{-1}$ – per degrees Celsius; µmole m^{-2} d^{-1} – micromoles per square meter per day; µmole m^{-2} s^{-1} – micromoles per square meter per second; d^{-1} – per day; gdw m^{-2} – grams dry weight per square meter; m – meters; m^{-1} – per meter; m^2 gdw^{-1} – square meters per grams dry weight; m^3 mg^{-1} – cubic meters per milligram; and NTU^{-1} – per nephelometric turbidity units.

Key to agencies: NOAA – National Oceanic and Atmospheric Administration and USGS – United States Geological Survey.



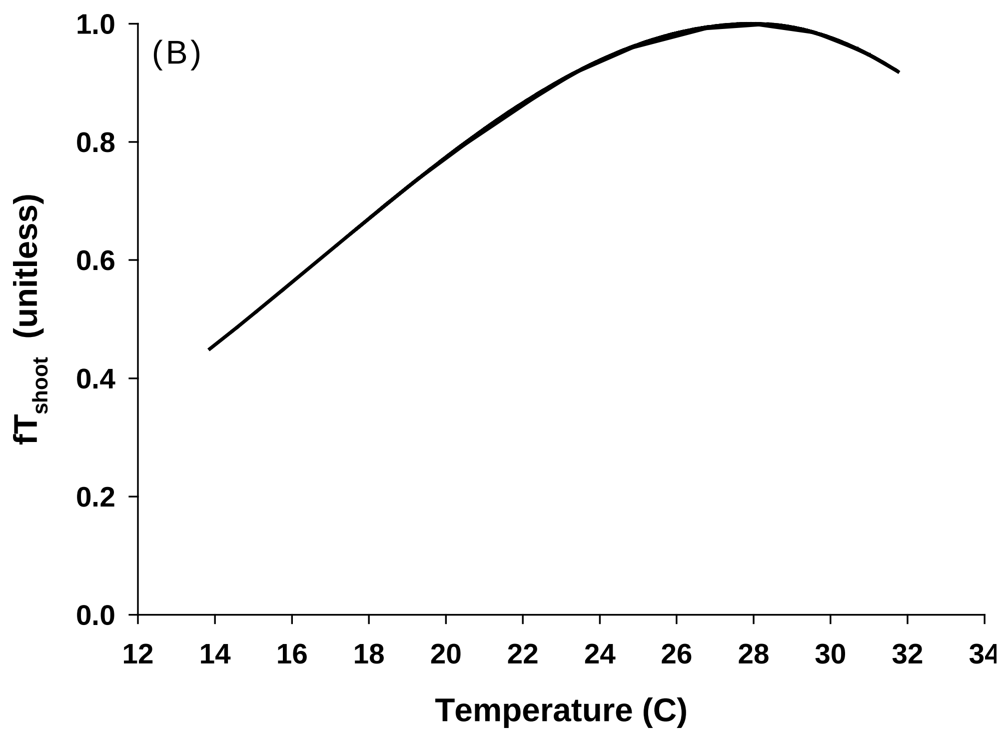


Figure A-47. (A) Time series of daily water temperature in °C at the Ft. Myers station from 1998 to 2012. (B) Relationship between water temperature in °C and the shoot gross production rate (fTshoot).

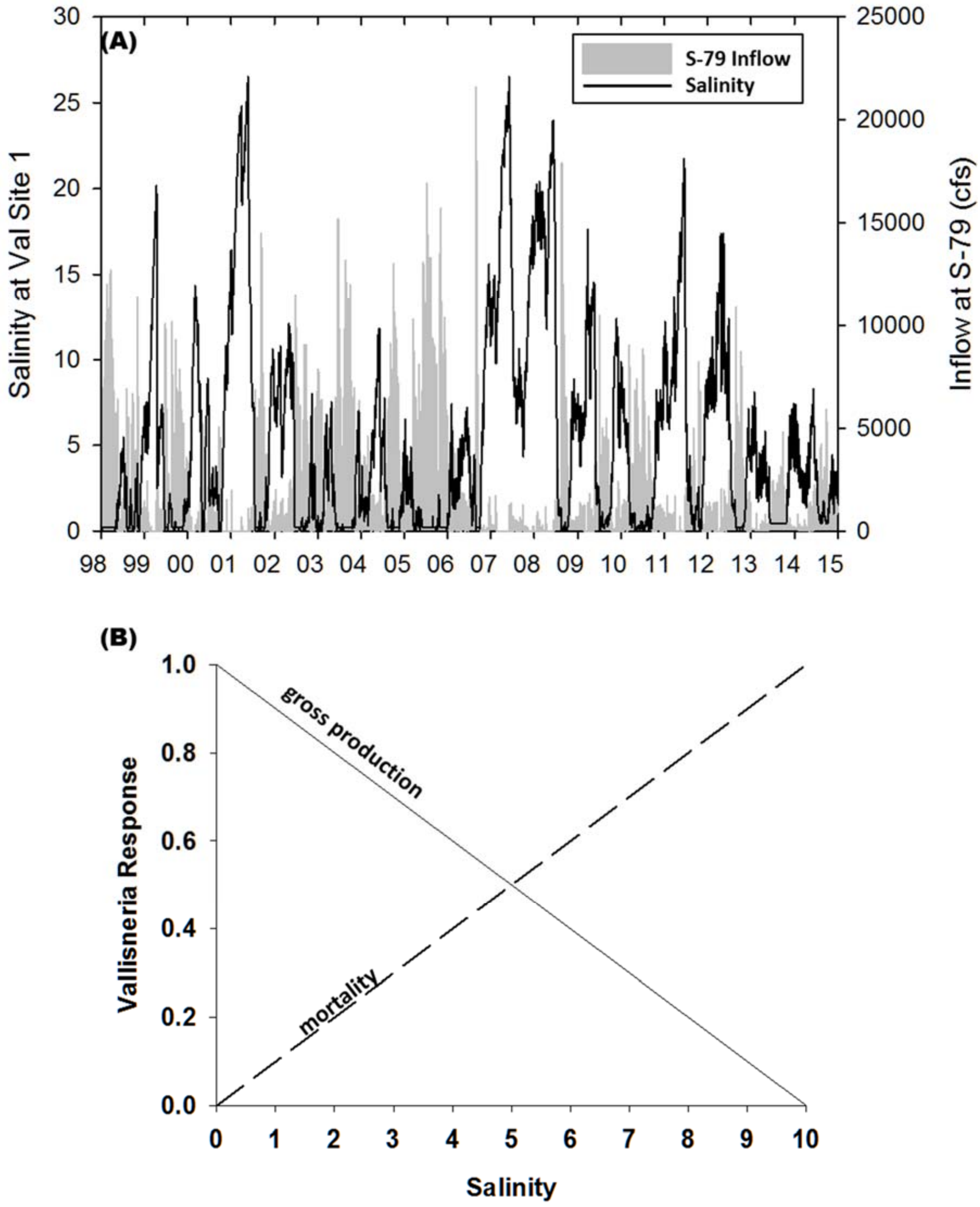


Figure A-48. (A) Time series of daily salinity predicted for SAV monitoring Site 1 from 1998 to 2014 (black line; left axis) and freshwater inflow at S-79 (cubic meters per second [$m^3 s^{-1}$]; grey fill; right axis). (B) Scalar multiplier for the negative effects of salinity on gross photosynthesis (fS_{gross}; solid) and positive effects on shoot mortality (fS_{loss}; dashed).

Irradiance at the water surface (I_0) and photoperiod (P_{photo}) were necessary to simulate variations in light (**Tables A-24** and **A-25**). Surface light was attenuated by water depth and the total attenuation coefficient to derive irradiance at the bottom (I_z). Variable water level (η) was calculated hourly based on the amplitude (AM2), period (TM2), and phase of the M2 tide (PhM2) determined for the Ft. Myers station (**Tables A-24** and **A-25**). Depth (h) was calculated as the difference between η and the base elevation of the habitat (z). The total attenuation coefficient for submarine light (k_t) contained contributions from pure water (k_w), color, turbidity (NTU), and chlorophyll *a* concentration (CHL) (Christian and Sheng 2003). Attenuation due to color (k_{color}) was estimated using a negative exponential relationship with salinity (**Tables A-24** and **A-25**); McPherson and Miller 1994, Buzzelli et al. 2012). Time series for monthly average NTU and CHL were derived from monitoring data at station CES04 (**Figures A-49A** and **49B**). These data are available through DBHYDRO (www.sfwmd.gov/science-data/dbhydro). There were specific coefficients for each of the attenuation components: k_w, attenuation factor for turbidity (a_{NTU}), attenuation factor for chlorophyll *a* (a_{CHL}), and constants for salinity-color relationship (a_{color} and b_{color}); (**Table A-25**). I_z in µmoles per square meter per second (µmoles m^{-2} s^{-1}) was calculated as an exponential decline with h depending upon k_t (**Tables A-24** and **A-25**). The percentage of surface irradiance at the bottom ($\%I_0$) is simply a ratio between the half-saturation irradiance value (I_k) and I_0 multiplied by 100 (**Tables A-24** and **A-25**).

The equations for *Vallisneria* were similar to those used in modeling of seagrass communities in the Southern Indian River Lagoon and the lower CRE (Buzzelli et al. 2012, 2014b). Changes in the aboveground biomass of *Vallisneria* (C_{shoot}) resulted from gross production (G_{shoot}), respiration (R_{shoot}), salinity-based mortality (M_{shoot}), and herbivorous grazing (Gz_{shoot}; **Table A-24**). G_{shoot} included terms for the maximum rate of photosynthesis (P_m), light limitation using I_k, gross production (fS_{gross}; **Figure A-48B**), photosynthesis-irradiance relationship (fT_{shoot}), and C_{shoot} (Buzzelli et al. 2012, 2014b). The rate was also scaled using the maximum biomass (C_{shoot}/C_{max}). P_m and I_k were set at 0.02 per day and 56 µmoles m^{-2} s^{-1}, respectively (**Table A-25**; Blanch et al. 1998). R_{shoot} included a basal rate of respiration (kR) and an exponential increase with water temperature (T_w; **Table A-25**). M_{shoot} was calculated using the basal rate of mortality (kM) combined with shoot mortality (fS_{loss}; **Figure A-48B**). Finally, the Gz_{shoot} was the product of a basal grazing rate (kGz) and the square of C_{shoot} (**Tables A-24** and **A-25**).

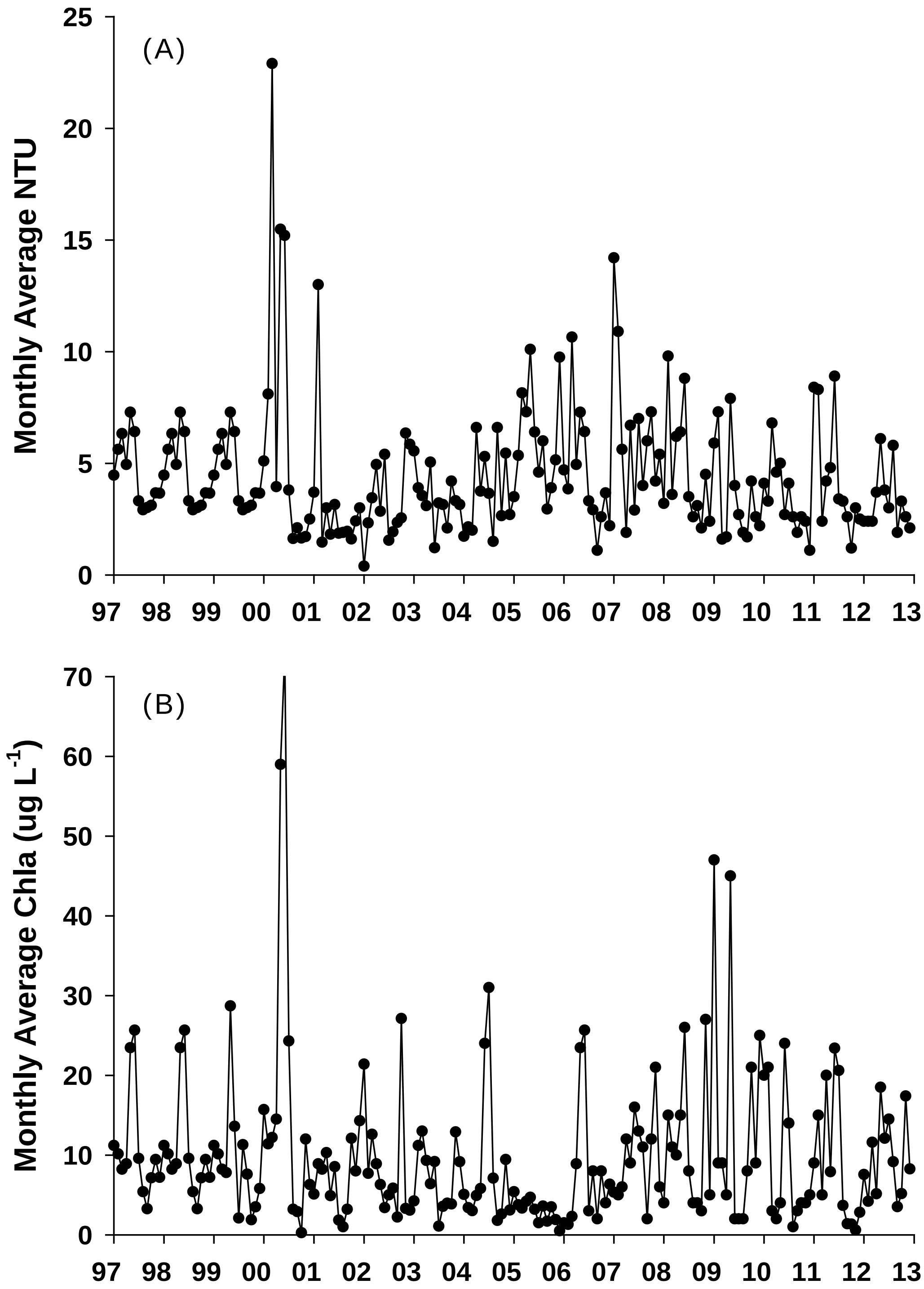


Figure A-49. Monthly time series at CES04 monitoring site in the CRE for (A) turbidity (NTU) and (B) CHL.

Model Calibration, Sensitivity, and Application

Vallisneria occurs naturally in a wide range of freshwater and estuarine environments from Maine to Texas and inland to the Mississippi River (McFarland 2006). Despite its prevalence, there have been few physiological studies through which to obtain essential rate constants for model development. Calibration exercises were mindful of the spatial variations in patch densities inherent in the natural community, unavoidable sampling bias during routine monitoring, variability in the mesocosm-derived relationship between shoot densities and biomass, and the lack of information on rates of mortality and grazing specific to the CRE.

The goal of calibration was to provide the best approximation of the biomass time series derived for Site 1 near Beautiful Island in the upper CRE. The simulation of *Vallisneria* shoot biomass was calibrated by adjusting initial biomass values (C_{init}), the salinity-specific loss rate (kS_{loss}), and kGz. C_{init}, P_m, kR, kS_{loss}, and kGz were varied by ±10% and ±50% relative to the base model values in a series of sensitivity tests.

In order to help describe the conditions that account for *Vallisneria* survival versus loss, the environmental variables (inflow, temperature, salinity, and light) and *Vallisneria* shoot biomass were evaluated for each dry season from 1998 to 2014. An eight-year experimental model was generated by looping the favorable environmental conditions (salinity, turbidity, and CHL) from the 1998–1999 calendar years (2 year x 4 loops = 8-year simulations). Salinity values for each day in the dry season were systematically increased by 5 to 75% at 5% intervals over 16 model runs (base model + 15 separate simulations; 7 of which are shown in **Figure A-50**). In order to identify the S-79 inflows associated with net morality of *Vallisneria*, the daily dry season salinity was systematically increased until shoot biomass at the end of the simulation was less than that at the beginning (i.e. net mortality). The resulting dry season salinity increase that led to net mortality was used to estimate the freshwater inflows using the annual regression equations from Component Study 2. Finally, the model was used to calculate the percentage of shoots lost based on the number of consecutive days where salinity was $\geq$ 10 in multiple dry seasons.

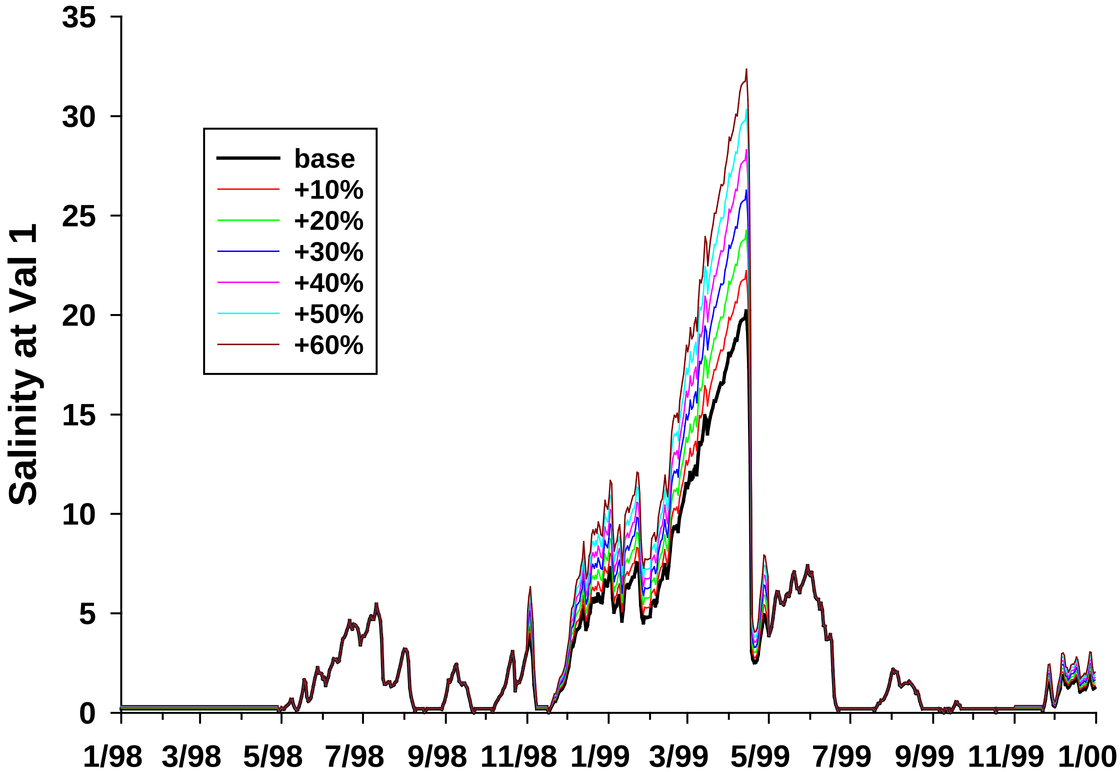


Figure A-50. Time series of altered daily salinity in the dry season as input to the 1998–1999 loop model.

Results

The model output was sensitive to changes in C_{init}, P_m, kR, kS_{loss}, and kGz. Predicted shoot biomass declined by -19.5 and -69.2% when P_m was decreased by -10 and -50%, respectively (**Table A-26**). The effects of increasing P_m by +10 and +50% were comparatively greater as model shoot biomass increased by +25.1 and +201.0%, respectively. Predicted shoot biomass increased by +8.6 and +52.9% when kR was decreased by -10 and -50%, respectively (**Table A-26**). The effects of increasing kR by 10 and 50% led to shoot biomass decreases of -7.7 and -32.0%, respectively. Adjustments in C_{init} had diminished effects on predicted shoot biomass relative to the other parameters. Decreased values for kS_{loss} resulted in the greatest relative increase in predicted biomass (72.7 and 861.5%, respectively). The effect of increasing kS_{loss} was less dramatic (-36.0 and -81.9%). Finally, decreasing kGz by -10 and -50% increased shoot biomass by 8.9 and 70.9%, respectively. Increasing kGz had a reduced negative effect (-7.5 and -28.5% for +10 and +50% increase in kGz, respectively).

Table A-26. Results of sensitivity tests for the effects of physiological coefficients on predicted *Vallisneria* shoot biomass.
(Notes: The maximum rate of photosynthesis [P_m; per day], the basal rate of respiration [kR; per day], the initial shoot biomass [C_{init}; gdw m^{-2}], the shoot loss rate due to salinity [kS_{loss}; per day], and the basal grazing rate [kGz; square meter per grams dry weight (m^2 gdw^{-1})] were varied by +10 and +50% in independent model simulations. Simulations spanned 18 years [1997–2014 = 6,574 days]. Provided are the coefficient values, the predicted biomass ranges [C_{shoot}; gdw m^{-2}], the average and standard deviations [Avg ± SD] of predicted biomass [gdw m^{-2}], and the percent difference between the base model values [base] and each sensitivity test averaged over all simulation days [%Difference = ((observed – expected)/expected)*100].)

Coefficient	Sensitivity Test	Coefficient Value	Range	Avg ± SD	%Difference
P_m	Base	0.020			
	-10%	0.018	0.1–32.0	5.0 ± 5.8	-19.5%
	-50%	0.010	0.0–14.9	2.2 ± 2.7	-69.2%
	+10%	0.022	0.15–38.1	6.7 ± 7.2	25.1%
	+50%	0.030	0.2–45.8	10.5 ± 9.7	201.0%
kR	Base	0.001			
	-10%	0.0009	0.1–36.1	6.1 ± 6.7	8.6%
	-50%	0.0005	0.2–38.8	7.2 ± 7.4	52.9%
	+10%	0.0011	0.1–34.6	5.6 ± 6.4	-7.7%
	+50%	0.0015	0.1–31.1	4.6 ± 5.6	-32.0%
C_{init}	Base	15.0			
	-10%	13.5	0.1–35.3	5.7 ± 6.5	-0.9%
	-50%	7.5	0.1–35.3	5.3 ± 6.3	-5.6%
	+10%	16.5	0.1–35.3	5.9 ± 6.6	0.8%
	+50%	22.5	0.1–35.3	6.1 ± 6.7	3.4%
kS_{loss}	Base	0.01			
	-10%	0.009	0.2–36.6	7.1 ± 6.9	72.7%
	-50%	0.005	1.9–39.3	14.0 ± 7.5	861.5%
	+10%	0.011	0.0–33.5	4.8 ± 6.0	-36.0%
	+50%	0.015	0.0–14.9	1.8 ± 2.8	-81.9%
kGz	Base	0.0002			
	-10%	0.00018	0.1–38.6	6.3 ± 7.1	8.9%
	-50%	0.0001	0.2–60.9	9.6 ± 11.0	70.9%
	+10%	0.00022	0.1–32.6	5.4 ± 6.1	-7.5%
	+50%	0.0003	0.1–24.9	4.2 ± 4.7	-28.5%

The average inflow rate through S-79 over all dry seasons averaged 1,172 cfs ranging from 52 ± 151 cfs (2008) to 5,596 ± 3,655 cfs (1998; **Table A-27**). S_{val1} averaged 6.9 ± 2.9 ranging from 1.2 (1998) to ~16.5 (2001 and 2008). An average of ~7% of surface irradiance reached the bottom including a minimum of 3.3% under the greatest inflows (1998) and a maximum of 15.7% when inflow was low (2001). Submarine light extinction ranged from a maximum of ~8.0 per meter (m^{-1}) (~0% surface irradiance) in 2000 to < 1.0 m^{-1} (> 30% surface irradiance) in 2001, 2008, and 2011 (**Figure A-51**). Light availability for *Vallisneria* was generally inversely related to freshwater inflow due to the dominant role of color (McPherson and Miller 1994, Buzzelli et al. 2014b, Chen et al. 2015). The exception occurred in May–June 2000 when the relative influences of both CHL and turbidity enhanced light extinction (**Figure A-49**).

Average *Vallisneria* shoot density at Site 1 was variable ranging from 0.0 to 325 shoots m^{-2} from 1998 to 2007 (**Figure A-52A**). Average density peaked in the wet seasons of 1998–1999 (200–300 shoots m^{-2}) and 2005–2006 (100–200 shoots m^{-2}). There was a decline approaching 0.0 in the 2000 dry season followed by an increase (~100 shoots m^{-2}) in the wet season before minimal shoots were observed from 2001 to 2003. Shoot density increased in the subsequent wet seasons before dry conditions in 2007 and into 2008 triggered widespread loss of shoots. The relationship between shoot density and biomass was used to generate the time series of aboveground biomass used to calibrate the model (gdw m^{-2}; $r^2 = 0.82$; **Figure A-52B** and **C**).

The model provided a reasonable approximation of the shoot biomass converted from the observed densities (**Figure A-53**). Although the model was sensitive to parameter values and over predicted the biomass for the 2006 dry season, it was a responsive indicator of changes in salinity. This was evident throughout the simulation period culminating in a slight increase in shoot biomass as conditions improved from 2013 to 2014.

Conditions from 1998 to 1999 were conducive for survival and growth of *Vallisneria* in the upper CRE (**Table A-27**). Salinity increases of 5% per trial led to a linear reduction in model biomass over the eight-year experimental simulations (**Figure A-54**). A 55% increase in dry season salinities resulted in a net decrease in shoot biomass at the end of the experimental simulation. The model experiment predicted that an average dry season salinity of 12 will result in net mortality of *Vallisneria* in the CRE. This value was used to estimate the associated freshwater inflows from the annual inflow-salinity relationships derived in Component Study 2. Estimated inflows associated with *Vallisneria* mortality ranged from 15 to 629 cfs (n = 14) averaging 342 ± 180 cfs.

The number of consecutive days where S_{val1} was ³ 10 ranged among 10 days (2002), 40–48 days (1999, 2000, 2009, and 2012), and 145–182 days (2001, 2007, and 2008; **Table A-28**). Model results suggested that an estimated 17.6% of the *Vallisneria* shoots were lost when salinity was ³ 10 for 10 consecutive days. This value increased to 85.4% (2001) and 86.7% (2007) when salinity was elevated for a majority of the dry season. Due to the losses in 2007, initial shoot density was not great enough to calculate changes with extended times of increased salinity in 2008–2012.

Table A-27. Dry season (November–April) average and standard deviations (Avg ± SD) for model variables from WY1998 to WY2014. (Notes: Variables include freshwater inflow at S-79 [Q_{S79}] and the tidal basin [Q_{TB}; cfs], salinity at *Vallisneria* monitoring site 1 [S_{val1}], temperature at Ft. Myers [T; °C], total light extinction coefficient [k_t; m^{-1}], the percentage of surface light at the bottom [$\%I_0$; unitless], and model *Vallisneria* shoot biomass [C_{shoot}; gdw m^{-2}]. The range of model *Vallisneria* shoot biomass for each dry season is also provided. See text for description of model input and response variables.)

Water Year	Q_{S79} (cfs)	Q_{TB} (cfs)	S_{val1}	T	k_t	$\%I_0$	C_{shoot}	
	Avg ± SD	Avg ± SD	Avg ± SD	Avg ± SD	Avg ± SD	Avg ± SD	Range	Avg ± SD
1998	5,596±3,655	1,024±679	1.2±1.9	21.3±2.5	3.6±0.5	3.3±1.4	7.8–12.2	9.2±2.8
1999	737±1,606	344±460	7.7±5.6	22.8±3.0	2.6±0.8	8.0±5.4	7.8–17.5	14.1±3.1
2000	1,412±1,766	147±135	5.5±4.6	21.7±2.9	3.5±1.0	4.3±2.5	7.6–18.5	13.5±3.4
2001	61±269	146±148	16.6±5.3	21.1±3.9	1.5±0.5	15.7±6.2	2.5–7.5	5.8±1.7
2002	440±462	125±110	7.4±2.4	22.5±3.5	2.5±0.4	7.6±2.9	1.5–3.0	2.5±0.4
2003	1,809±1,948	306±271	2.7±2.4	21.7±3.9	3.2±0.6	4.9±2.4	2.2–4.9	3.9±0.9
2004	1,358±1,360	198±190	2.8±2.0	21.1±2.9	2.9±0.4	5.3±1.7	9.8–16.4	13.6±1.7
2005	2,212±1,991	185±209	1.8±1.5	21.1±3.0	3.2±0.4	4.2±1.0	11.3–18.7	15.5±1.8
2006	3,273±3,552	185±220	2.0±1.8	21.7±3.1	3.5±0.4	3.5±1.0	17.2–35.3	26.6±5.3
2007	128±262	120±102	14.7±3.9	21.5±2.4	1.8±0.3	11.9±2.9	3.5–17.1	10.3±4.6
2008	52±151	148±132	16.5±2.2	22.2±2.7	1.9±0.5	11.4±3.5	0.3–1.1	0.8±0.3
2009	426±340	130±121	8.1±3.1	20.9±3.0	2.9±1.2	7.5±5.9	0.2–0.4	0.3±0.1
2010	1,117±1,448	344±401	5.6±3.7	20.4±3.3	2.9±0.8	5.9±2.6	0.2–0.4	0.3±0.1
2011	268±371	164±171	8.7±2.2	21.2±4.4	2.6±0.5	7.0±2.8	0.4–1.3	0.9±0.3
2012	488±695	256±304	8.2±3.9	22.4±2.5	2.4±0.5	8.4±3.3	0.2–0.8	0.5±0.2
2013	371±534	162±141	4.0±1.6	21.7±2.6	3.5±0.8	4.0±2.6	0.3–0.5	0.4±0.1
2014	168±145	168±145	4.0±1.5	22.2±2.8	3.2±0.5	4.6±1.4	1.4–2.0	1.6±0.2
Total	1,172±1,117	244±154	6.9±2.9	21.6±3.1	2.8±0.6	6.9±2.9		7.1±1.6

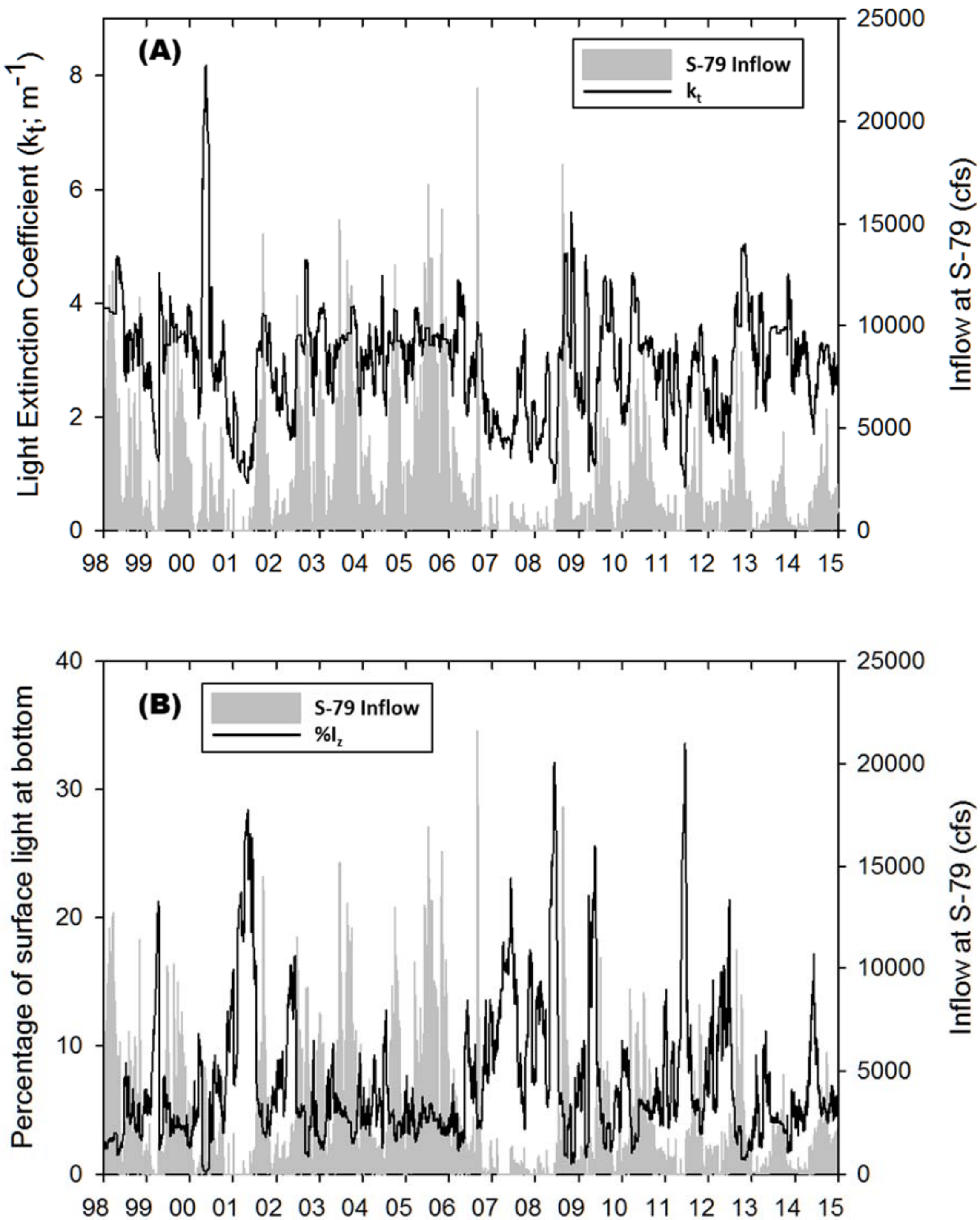


Figure A-51. (A) Time series of the submarine light extinction coefficient (k_t; m^{-1}; left axis) and daily freshwater inflow at S-79 (cfs; right axis). (B) Time series of the percent of light at the bottom ($\%I_0$; left axis) and daily freshwater inflow at S-79 (cfs; right axis).

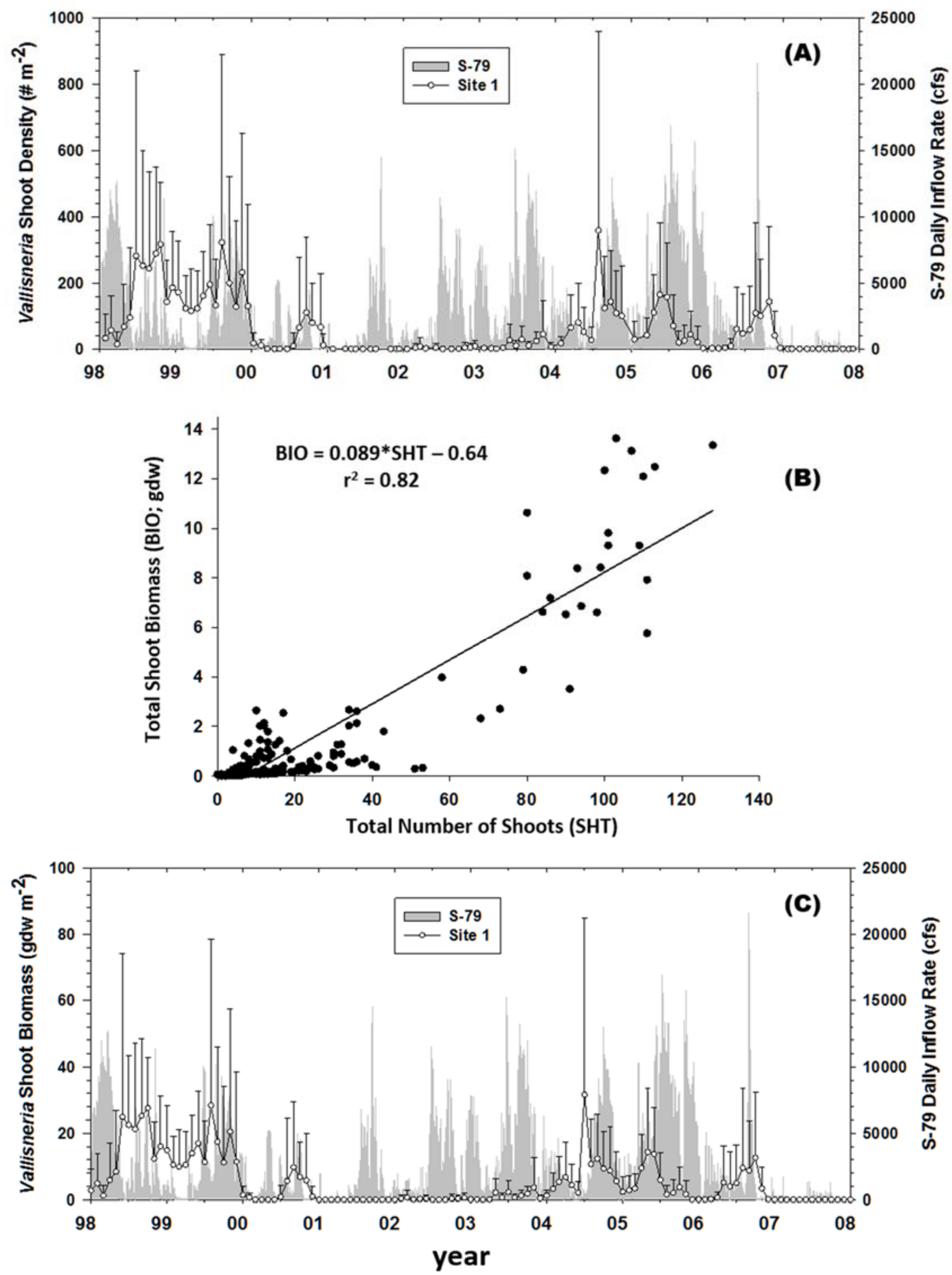


Figure A-52. (A) Time series of *Vallisneria* shoot density (average + standard deviation) from Site 1 near Beautiful Island in the CRE. (B) Linear regression between total number of *Vallisneria* shoots and total dry weight biomass of shoots (grams dry weight [gdw]) from controlled mesocosm experiments. (C) Time series of Site 1 *Vallisneria* shoot biomass (average + standard deviation) derived by converted shoot density using the regression equation.

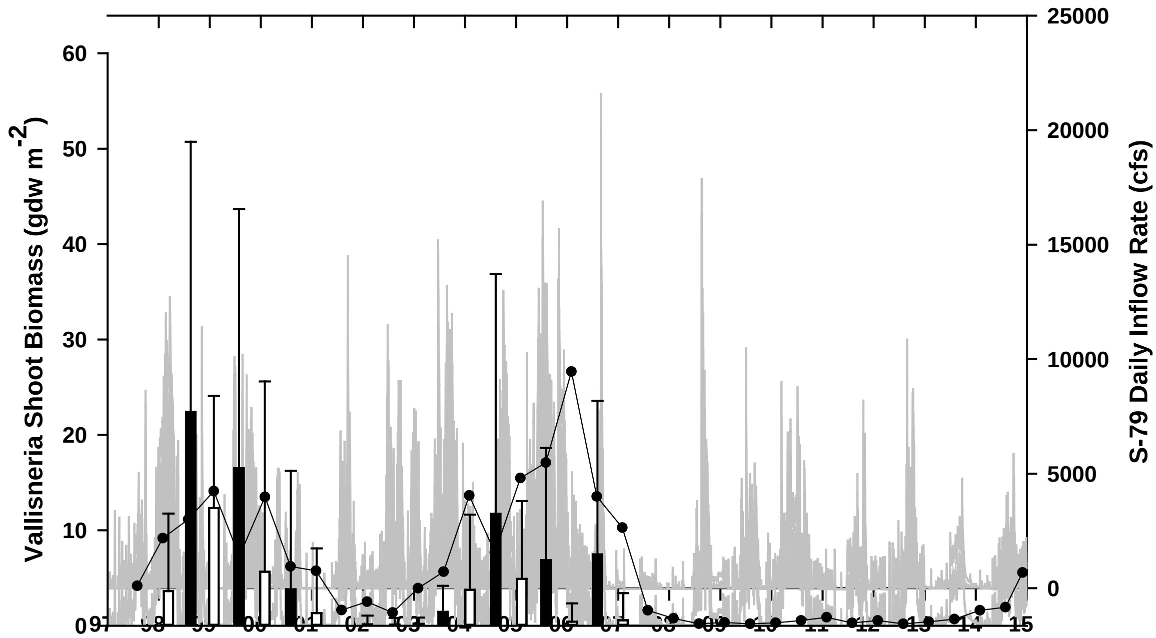


Figure A-53. Time series (1998–2014) of average seasonal *Vallisneria* shoot biomass from the model superimposed on average seasonal values at Site 1 (1998–2008). (Note: Daily inflow at S-79 shown as shaded area with right axis.)

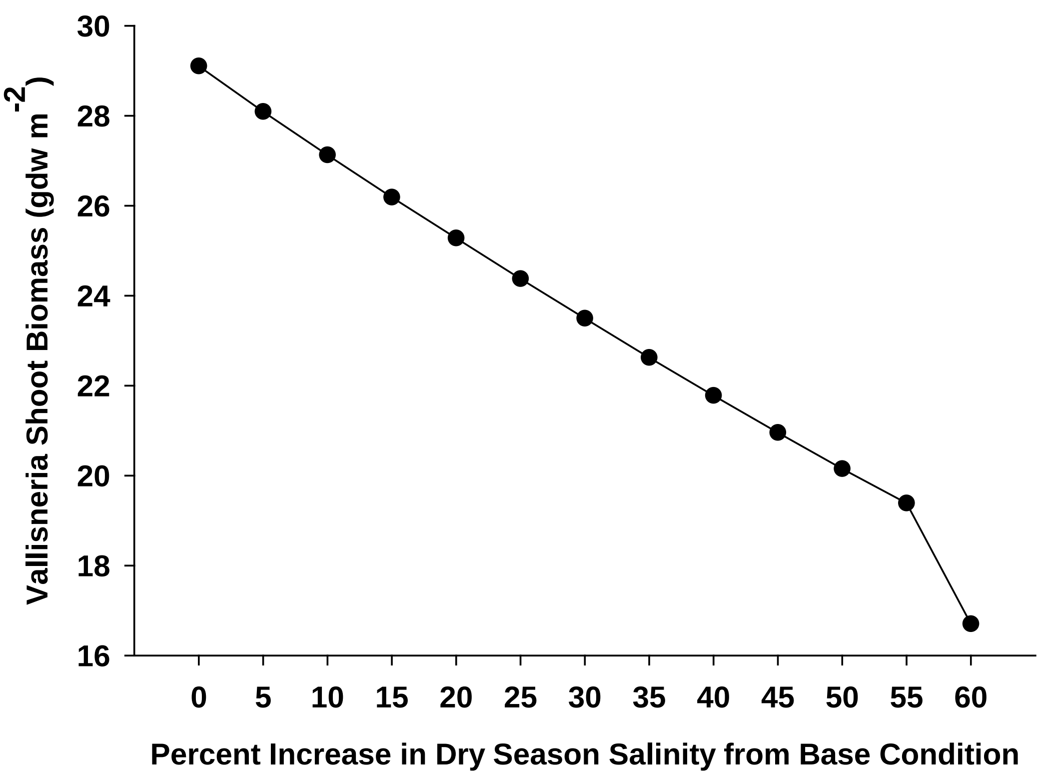


Figure A-54. Plot of percent increase in dry season salinity versus average shoot biomass. A 55% increase in dry season salinity values resulted in net mortality of *Vallisneria*.

Table A-28. Results from a simulation model of *Vallisneria*.
(Notes: Shown are dry seasons with average daily salinities ³ 10 at Monitoring Site 1 in the CRE from WY1999 to WY2012. All values are based on daily salinity ³ 10 including the total number of days in the dry season, the average and standard deviation [Avg ± SD] of salinity for those days, the initial and final dates bracketing consecutive days where salinity was ³ 10, the initial shoot density, and the percentage of initial shoots lost during the consecutive days. The model biomass reaches a minimum of 0.1 gdw m^{-2}, which converts to ~8 shoots m^{-2}.)

Water Year	Total Number of Days S_{val1} ³ 10	Salinity Avg + SD	Initial Date	Final Date	Consecutive Days S_{val1} ³ 10	Initial Shoot Density (# m^{-2})	% Shoots Lost
1999	53	15.4 ± 3.0	3/1/99	4/17/99	48	283	54.8%
2000	42	12.3 ± 1.2	2/17/00	3/29/00	42	222	47.3%
2001	150	18.3 ± 4.2	12/6/00	4/30/01	145	110	86.7%
2002	19	10.5 ± 0.4	4/21/02	4/30/02	10	11	17.6%
2007	174	14.9 ± 3.8	11/7/06	4/30/07	174	72	85.4%
2008	182	16.5 ± 2.2	11/1/07	4/30/08	182	9	5.4%
2009	46	12.8 ± 1.7	3/10/09	4/30/09	46	-	-
2010	26	11.1 ± 0.6	11/10/09	12/5/09	26	-	-
2011	47	11.7 ± 1.3	4/12/11	4/30/11	18	-	-
2012	50	12.9 ± 2.1	3/16/12	4/24/12	40	-	-

Discussion

The incorporation of the environmental requirements of *Vallisneria* into a resource-based approach to estuary and water management is very unique in estuarine science (Doering et al. 2002). This uniqueness emerges because (1) freshwater inflow from S-79 has been regulated since 1966; (2) low freshwater inflow in the dry season can lead to increased salinity throughout the estuary; (3) historically, *Vallisneria* habitat has been an important ecological resource in the upper CRE; and (4) *Vallisneria* sensitivity to salinity at weekly-annual time scales makes it an excellent indicator of managed freshwater inflows. This study built upon existing information to derive a model to simulate the responses of *Vallisneria* to environmental drivers (i.e. temperature, salinity, and light; Doering et al 1999, 2002, French and Moore 2003, Bartleson et al. 2014). Ecological modeling provides a pathway to incorporate the effects of multiple non-linear variables, evaluate different management alternatives, and build consensus among a variety of stakeholders (Costanza and Ruth 1998, Urban 2006, Buzzelli et al. 2015b).

The *Vallisneria* model exhibited greater sensitivity to changes in parameter values than equivalent models of seagrasses in South Florida (Buzzelli et al. 2012, 2014b). The enhanced sensitivity of the *Vallisneria* model resulted because small changes in salinity (i.e. 4 to 5) triggered large changes in photosynthesis and mortality (> 10%). By comparison, the same salinity change would alter these rates by < 3% in the model of the seagrass *Syringodium filiforme* (Buzzelli et al. 2012). Since the P_m was determined experimentally (Blanch et al. 1998), calibration focused on adjusting the basal loss rates of mortality (kS_{loss}) and grazing (kGz) to best approximate the observed shoot attributes. The present model calibration provides a suitable representation of the responses of *Vallisneria* to fluctuations in salinity from 1998 to 2014.

The combination of the environmental drivers, field monitoring data, and the calibrated model indicated that salinity was indeed the key variable affecting the survival and growth of *Vallisneria*. Although only 3 to 8% of submarine light reached the bottom, dry season salinity conditions in

1998–2000 and 2004–2006 promoted the production of shoot biomass. In contrast, an average of 11 to 15% of submarine light was available in the drought years of 2001 and 2007–2008 when *Vallisneria* declined. There were intra- and interannual patterns between inflow, salinity, and *Vallisneria*. Periods where *Vallisneria* biomass increased generally spanned 4 to 6 months indicative of wet season conditions with increasing freshwater inflow and decreasing salinity. Each of these periods of favorable conditions started in June or July with salinity values ranging from ~1.0 to 2.0. Periods where *Vallisneria* biomass decreased generally spanned 6 to 8 months indicative of dry season conditions that extended into May–July of the following calendar year.

The model provided an effective tool to explore and quantify both freshwater inflow and the duration of high salinity conditions that contribute to the mortality of *Vallisneria* in the CRE. While the field monitoring and Ft. Myers salinity data were used to estimate that inflows of at least 545 ± 774 cfs were associated with *Vallisneria* survival from 1993 to 1999 (Component Study 7), the model was used to specify the freshwater inflow associated with net mortality (342 ± 180 cfs). Furthermore, the model results demonstrated that ~50% of the *Vallisneria* shoots were lost when salinity in the *Vallisneria* habitat near Beautiful Island was $\geq$ 10 for ~1 month. These results provide a quantitative base to assess freshwater inflow requirements for the CRE.

Component Study 9: Assessment of Dry Season Salinity and Freshwater Inflow Relevant for Oyster Habitat in the CRE

Christopher Buzzelli, Cassondra Thomas, and Peter Doering

Abstract

Short- and long-term alteration of salinity distributions in estuaries with variable freshwater inflow affects the survival, abundance, and extent of oyster habitat. The objective of this study was to evaluate salinity conditions at two locations (Cape Coral and Shell Point) in the CRE. Salinity data from the 2006–2014 dry seasons (November–April) were categorized relative to oyster habitat criteria and related to freshwater inflow. Daily salinity was within the appropriate range for oysters (10– 25) on 70.1% of the observations. Daily inflow ranged from 0 to 2,000 cfs and averaged 296 ± 410 cfs when salinity ranged from 20 to 25 at Cape Coral in the dry season. The influence of the marine parasite *Perkinsus marinus* (Dermo) is limited due to the subtropical climate where temperature is low when salinity is high (dry season) and temperature is high when salinity is low (wet season). Overall salinity patterns were favorable for oyster survival at the upstream extent of oyster habitat in the CRE.

Introduction

The distribution and abundance of eastern oyster (*Crassostrea virginica*) habitat provides an ecosystem-scale indication of estuarine status (Kemp et al. 2005). Oysters filter suspended solids coupling the benthos to the water column while providing habitat for a variety of fauna (Tolley et al. 2006, Coen et al. 2007). The survival and growth of oysters are influenced by covariations in temperature, salinity, food supply, and mortality (Stanley and Sellers 1986, Bataller et al. 1999). Oyster habitat is declining worldwide through multiple interactive factors including over harvesting, disease, sedimentation, and altered salinity patterns (Beck et al. 2011).

Salinity is a primary environmental factor affecting the eastern oyster in the Gulf of Mexico estuaries with optimal values varying from 10 to 30 (Shumway 1996, Livingston et al. 2000, Barnes et al. 2007, Wang et al. 2008; **Table A-29**). A functioning oyster habitat is composed of the population cohorts (larvae, juvenile, and adults), protistan parasites (e.g. *Perkinsus marinus* or Dermo), the epibiotic community, and resident and transient consumers each with particular life histories and salinity tolerances (Dekshenieks et al. 2000, Tolley et al. 2006). Because the oyster life cycle is sensitive to both the timing and magnitude of variations in salinity, evaluating potential responses of oyster habitat to variable freshwater inflow offers a biotic tool for water management (Chamberlain and Doering 1998b, Volety et al. 2009).

Conventional wisdom suggests reduced freshwater inflow leads to increased salinity, which negatively impacts oyster populations (Powell et al. 2003, Turner 2006). The introduction of marine parasites and predators is assumed to account for oyster losses (Stanley and Sellers 1986, Livingston et al. 2000, Powell et al. 2003, LaPeyre et al. 2003, Buzan et al. 2009, Petes et al. 2012). However, while episodic freshwater inputs reduce parasite activity, oyster filtration rates also can be suppressed by decreased salinity (Pollack et al. 2011). The ability of oysters to close their shells and alter pumping rates allows them to survive under fluctuating salinities (Loosanoff 1953, Davis 1958, Andrews et al. 1959). Patterns can be complicated as both oyster condition and long-term harvests around the Gulf of Mexico are positively correlated to salinity (Turner 2006, Guillian and Aguirre-Macedo 2009).

Table A-29. Summary of salinity tolerances for different oyster life stages.

Life Stage	Salinity Ranges			Citation
	Optimal	Sub-Optimal	Lethal	
Spawning	^{3} 12		0–10,40	Woodward-Clyde 1999, RECOVER 2014
Egg Development	23–29	5–32		Clark 1935
Larvae	23–27	12–32	< 12	Kennedy 1991, Dekshenieks et al. 1993, 1996
Spat				
Survival	10–27.5	5–32	< 5	Loosanoff 1953, RECOVER 2014
Setting	16–18	9–29		Loosanoff 1965, Kennedy 1991
Juvenile				
Survival	10–20	5–32		Woodward-Clyde 1999
Predation Avoidance	< 20		20–25	Butler 1954, Wells 1961, Mackin and Hopkins 1962, Galtsoff 1964, Zachary and Haven 1973
Adult				
Survival	10–30	5–40	< 7	Loosanoff 1953, Mackin and Hopkins 1962, Brown and Hartwick 1988, Fisher et al. 1996
Disease avoidance	< 5			La Peyre et al. 2009

Turner (2006) hypothesized that the effects of salinity on oyster yields depend upon both the historical conditions and current trajectory for salinity in a particular estuary. It has been suggested that increasing total freshwater input to the Gulf of Mexico estuaries for natural resource protection probably would not increase estuarine oyster harvests (Hofstetter 1977, Turner 2006). Therefore, short- and long-term alteration of salinity distributions in Gulf of Mexico estuaries with variable inflow can have implications for oyster survival, abundance, and habitat extent (Chamberlain and Doering 1998a, Wang et al. 2008, Volety et al. 2009, Pollack et al. 2011).

The objective of this research component was to evaluate salinity conditions at two locations with oyster habitat in the CRE. The two locations are Cape Coral and Shell Point near the mouth of the CRE (**Figure A-55**). Salinity data from the 2006–2014 dry seasons (November–April) were categorized relative to oyster habitat criteria and related to freshwater inflow at S-79 at the head of the CRE.

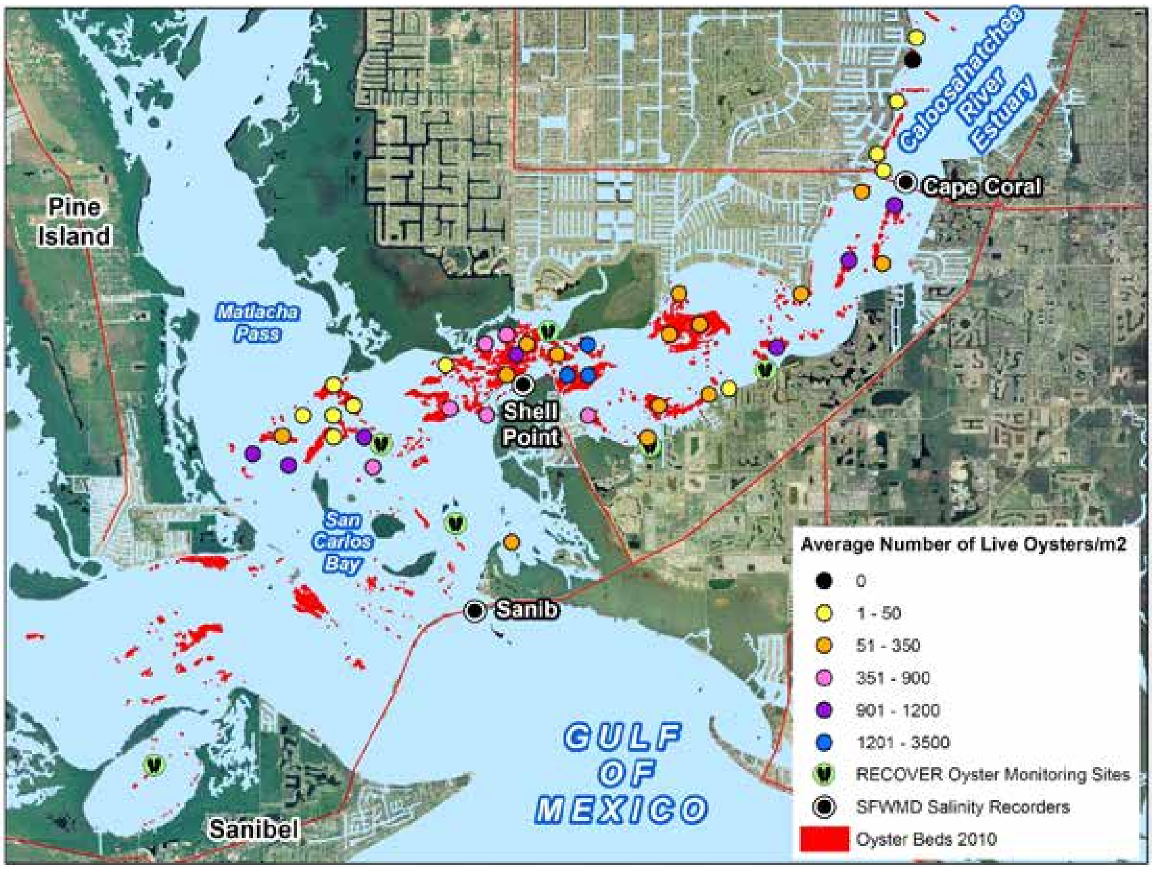


Figure A-55. Location map for Cape Coral and Shell Point sampling sites, oyster habitat derived from side-scan mapping (red), and average densities (colored circles) in the lower CRE.

Methods

Oyster habitat in the CRE was mapped in 2010 using side-scan sonar as part of CERP implementation (RECOVER 2012). This effort resulted in estimates of the extent and magnitude of oyster habitat. The benthic sampling effort used a four-prong approach: (1) calibration of the side-scan sonar and Quester Tangent Sideview Classification software in known oyster reef areas with varying substrate types, (2) remote sensing, (3) field intensive groundtruth data to classify benthic habitat types, and (4) extensive mapping and quantitative assessment of live and dead reefs and oyster shell lengths of live oyster reefs. The mapping effort resulted in an estimated 847 acres (3.7%) of bottom classified as "oyster" habitat in the lower CRE. Although there were isolated patches located in the middle estuary, the upstream limit for mapped oyster habitat was near Cape Coral. Oyster habitat was denser and more widespread near Shell Point (**Figure A-55**).

Salinity data collected at Cape Coral and Shell Point were used to assess estuarine conditions for oyster habitat. The POR for salinity data matched that for the monitoring of oyster population attributes in the CRE (2005–2014). Average daily salinity values at these locations were merged with average daily freshwater inflow at S-79. These data were used to generate time series (daily) and regressions between inflow and salinity at each station (monthly). Additionally, the data were categorized by water year and season (dry versus wet) with analyses focused on the dry season days.

In general, oyster growth and survival are maximized if salinity varies from 10 to 25 (**Table A-29**; Loosanoff 1953, Shumway 1996, Dekshenieks et al. 2000, Barnes et al. 2007). A conceptual model of oyster responses to salinity and freshwater inflow was developed for the CRE (**Figure A-56**; Buzzelli et al. 2013c). Based on this conceptualization, salinity data at Cape Coral and Shell Point were split into five categories: < 10, 10–15, 15–20, 20–25, and > 25. The number and percentage of dry season days where salinity values were within each of these categories were calculated. The averages and standard deviations for salinity and freshwater inflow associated with each of these salinity classes were also calculated for each of the downstream locations. The freshwater inflow associated with dry season salinity values of 20 to 25 at the upstream extent of oyster habitat (e.g. Cape Coral) was quantified.

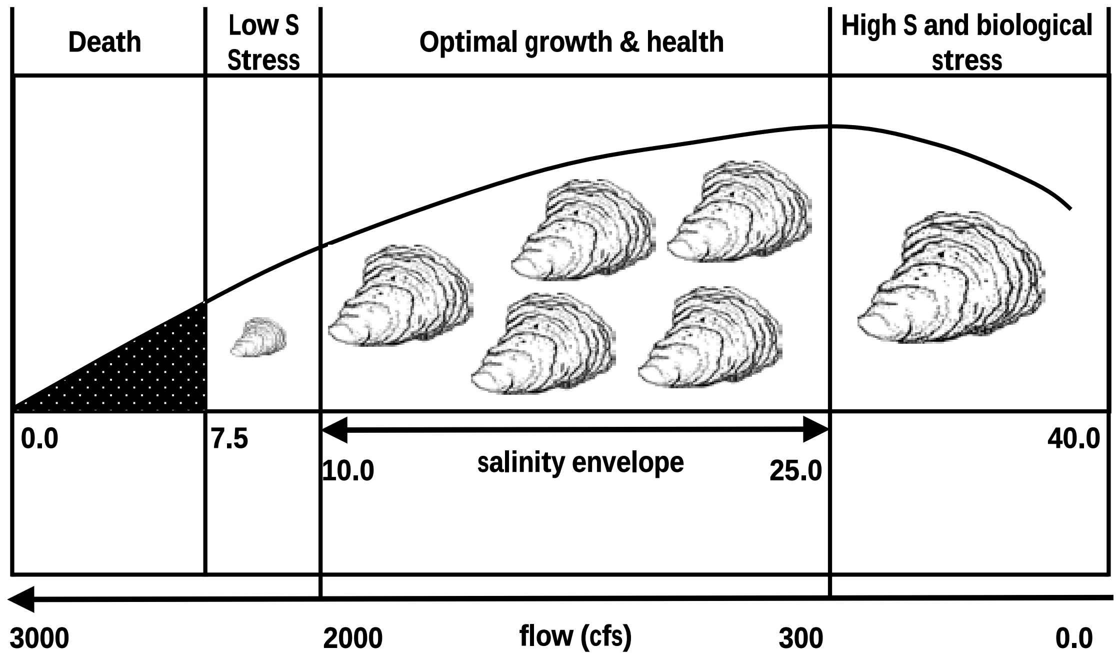


Figure A-56. Conceptual model of the effects of salinity (S) on oyster survival and growth. Generalized freshwater inflows that could account for the target salinity range are shown at the bottom.

Results

Freshwater inflow ranged from near zero to > 20,000 cfs throughout the POR (**Figure A-57**). Salinity at both locations increased with decreased inflow as the highest values were observed from January 2007 to August–September 2008. On average, salinity at Shell Point was ~1.5 times greater than at Cape Coral. Dry season salinity ranged from 1.1 to 32.2 and averaged 19.8 ± 5.7 at Cape Coral (**Table A-30**). Wet season salinity at Cape Coral ranged from 0.1 to 33.0 and averaged 12.6 ± 9.9. At Shell Point, salinity ranged from 12.0 to 36.9 and averaged 29.1 ± 4.1 in the dry season and 1.0 to 37.4 and 23.4 ± 8.6 in the wet season.

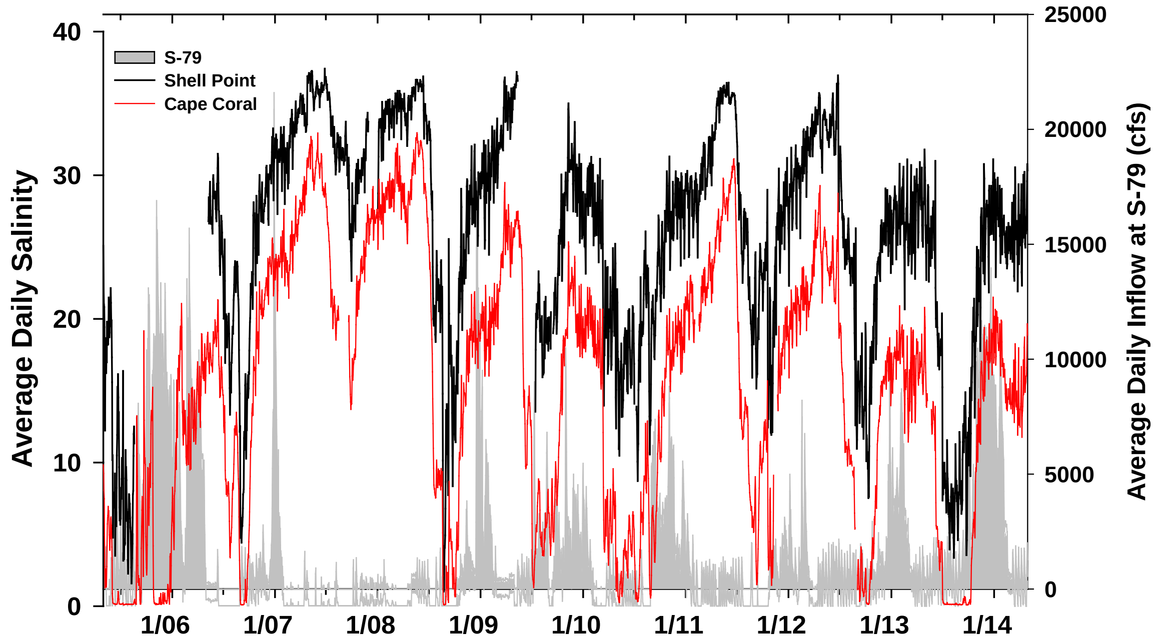


Figure A-57. Time series of average daily freshwater inflow at S-79 (cfs; right axis; shaded fill) and salinities at Cape Coral (red) and Shell Point (black) from May 1, 2005, to April 30, 2014.

Table A-30. Seasonal ranges, averages (Avg), and standard deviations (SD) for salinity values recorded at Cape Coral and Shell Point from 2005 to 2014.

Station	Season	Range	Avg ± SD
Cape Coral	Dry	1.1–32.2	19.8 ± 5.7
	Wet	0.1–33.0	12.6 ± 9.9
Shell Point	Dry	12.0–36.9	29.1 ± 4.1
	Wet	1.0–37.4	23.4 ± 8.6

Salinity was < 10 at Cape Coral for 234 or 13% of dry season days from 2005 to 2014 (**Table A-31**). By contrast, there were 299 days (16.8%) where salinity was > 25 at this location. The average and standard deviation for freshwater inflow were 90 ± 273 cfs when dry season salinity was > 25. Daily salinity was within the desired range for oyster survival (10 to 25) on 70.1% of the observations. Daily inflow ranged from 0 to 2,000 cfs and averaged 296 ± 410 cfs when salinity ranged from 20 to 25 at Cape Coral in the dry season. While dry season salinity was never < 10 at Shell Point, it exceeded 25 for 1,266 or 83.3% of the days (**Table A-32**). Salinity at Shell Point was within the 10 to 25 range on 16.8% of the days within the POR.

Table A-31. The number (n) and percentages (%) of dry season days with measured average (Avg) daily salinity values (± standard deviation [SD]) at Cape Coral that were < 10, 10–15, 15–20, 20–25, and > 25 from 2005 to 2014. (Note: Included are descriptive statistics [range and Avg ± SD] for salinity and freshwater inflow at S-79 (cfs) for each salinity class.)

Salinity Class	n	%	Salinity		Inflow at S-79	
			Range	Avg ± SD	Range	Avg ± SD
<10	234	13.1	0.15-10.0	4.5 ± 3.3	0–15,700	4,002 ± 2,984
10–15	221	12.4	10.1-15.0	13.2 ± 1.4	0–9,030	1,068 ± 981
15–20	606	34.0	15.0-20.0	17.6 ± 1.4	0–6,990	670 ± 693
20–25	422	23.7	20.0-25.0	22.3 ± 1.4	0–2,000	296 ± 410
>25	299	16.8	25.0-32.2	27.7 ± 1.6	0–2,030	90 ± 273
Total	1782	100.0	0.15-32.2	18.1 ± 7.1	0–15,700	967 ± 1,721

Table A-32. The number (n) and percentages (%) of dry season days with measured average (Avg) daily salinity values [± standard deviation (SD)] at Shell Point that were < 10, 10–15, 15–20, 20–25, and > 25 from 2005 to 2014. (Notes: Included are descriptive statistics [range and Avg ± SD] for salinity and freshwater inflow at S-79 [cfs] for each salinity class. NA – not applicable.]

Salinity Class	n	%	Salinity		Inflow at S-79	
			Range	Avg ± SD	Range	Avg ± SD
<10	0	0.0	NA	NA	NA	NA
10-15	13	0.9	10.3–14.9	13.1 ± 1.4	264–10,030	4,696 ± 2,760
15-20	62	4.1	15.1–20.0	17.9 ± 1.4	256–5,990	2,537 ± 1,449
20-25	179	11.8	20.1–25.0	23.2 ± 1.3	0–9,030	1,243 ± 1,203
>25	1266	83.3	25.0–36.9	30.0 ± 3.0	0–6,990	428 ± 567
Total	1520	100.0	10.3–36.9	28.6 ± 4.4	0–15,700	967 ± 1,721

Discussion

Overall salinity patterns were favorable for oyster survival at the upstream extent of oyster habitat in the CRE (i.e. Cape Coral). Dry season salinity averaged 19.8 and was within the 10 to 25 range ~70% of the time. Oyster habitat is more widespread with average densities of ~1,000 oysters m^{-2} in the lower CRE around Shell Point. This is despite the fact that salinity exceeded 25 for > 80% of the time in this location. Thus, the assertion that salinity values > 25 are potentially detrimental to oysters in the lower CRE was difficult to support.

The historical contention that increased salinity can negatively affect oyster populations may not be relevant for oyster habitat in the CRE. This contention is supported by studies in the northern Gulf of Mexico that demonstrated that an upper salinity threshold of 17 to 25 could damage oysters in Apalachicola Bay (Petes et al. 2012). Damage occurs through the increased activity and prevalence of the marine, oyster-specific disease Dermo as an impediment to the health, distribution, and density of oysters. However, this may be limited in the CRE due to the subtropical climate where temperature is low when salinity is high (dry season), and temperature is high when salinity is low (wet season). This contrast greatly inhibits the impact of Dermo. In fact, laboratory experiments, field studies, and simulation models support this understanding (LaPeyre et al. 2003, Buzzelli et al. 2013c). While Dermo can be detected in large percentage of individual oysters from the monitoring locations in the lower CRE, infection intensity levels are generally very low (RECOVER 2014).

Using oyster habitat properties as indicators of inflow and salinity in the CRE might be limited. First, the influence of freshwater inflow on salinity is reduced in polyhaline (18 to 30) areas of estuaries including the CRE (Qiu and Wan 2013). This is due to the effects of tidal exchange and wind on patterns of circulation. Most of the oyster habitat is located ~40 km downstream from the dominant source of freshwater inflow (S-79). Second, the effects of the marine parasite Dermo on oyster populations are muted. Third, the role of predators with increased salinity in the CRE is largely unknown.

Component Study 10: Ecohydrological Controls on Blue Crab Landings and Minimum Freshwater Inflow to the CRE

Peter H. Doering and Yongshan Wan

Abstract

A long-term record (28 years) was used for blue crab landings in the CRE to establish relationships between (1) changes in hydrology and changes in water resource function and (2) the magnitude of the functional loss and time to recover. Annual catch per unit effort (CPUE), computed from monthly landings of crabs and measures of fishing effort, represented the resource function. Annual landings expressed as both unadjusted and de-trended CPUE were found to be significantly correlated with hydrologic variables, rainfall and freshwater inflow, during the previous year's dry season. Increases in CPUE from one year to the next were also positively related to dry season rainfall in the first of the two years. Geometric mean functional regressions and Monte Carlo simulations were used to identify the dry season rainfall associated with losses of water resource function (CPUE) that required 1, 2, or 3 years of average dry season rainfall to recover. A spectral analysis indicated that time series of both dry season rainfall and blue crab catch had periodicities of 5.6 years. A Monte Carlo analysis revealed that the rainfall associated with two and three year recoveries had return intervals of 5.8 and 8.2 years, respectively.

Introduction

Estuaries are among the most productive (Nixon et al. 1986) and economically important ecosystems on earth, supporting both commercial and recreational fisheries (Copeland 1966, Seaman 1988). The critical role of freshwater inflow in supporting estuarine productivity is well recognized (Copeland 1966, Nixon 1981, Nixon et al. 2004, Wetz et al. 2011, Montagna et al. 2013). In the early 1970s, Sutcliffe (1972, 1973) presented correlations between discharge from the St. Lawrence River and lagged landings of lobster, halibut, haddock, and soft shell clams from the Gulf of St. Lawrence. These relationships established a link between freshwater discharge and production at higher trophic levels.

Since that time, numerous studies have found similar correlations between river discharge or rainfall and recruitment or catch of fish and shell fish (Drinkwater and Frank 1994, Robins et al. 2005) including in Florida for pink shrimp (Browder 1985), blue crabs, and oysters (Meeter et al. 1979, Wilber 1992, 1994). Reductions in freshwater inflow from droughts (Dolbeth et al. 2008, Wetz et al. 2011) and the construction of dams (Aleem 1972, Baisre and Arboleya 2006) have been associated with reduced fisheries landings. These studies suggest that correlations between river flow and rainfall and fish catch are real rather than spurious. While the underlying mechanisms accounting for these correlations are not clearly understood, Robins et al. (2005) reviewed the literature and identified the following three hypotheses: (1) The food chain hypothesis is basically an agricultural argument whereby nutrients in freshwater discharge enhance food supplies resulting in better growth and survival (e.g. Loneragan and Bunn 1999); (2) a hydrodynamically-based alternative argues that freshwater discharge and the associated circulation may increase the size of retention areas and enhance recruitment (Gillanders and Kingsford 2002); and (3) inflows may change spatial distribution and influence catchability (Loneragan and Bunn 1999).

In the State of Florida, water resource protection rules are often based on harm standards. An MFL rule protects a waterbody from "significant harm" caused by further withdrawals. Significant harm "means the temporary loss of water resource functions, which result from a change in surface or ground water hydrology, that takes more than two years to recover…" (Subsection 40E-8.021(31), F.A.C.). Establishing a water resource protection rule requires quantitative relationships between (1) changes in hydrology and changes in resource function and (2) the magnitude of resource loss and time to recover. Most of the MFLs rules that SFWMD has established contain a "return frequency" (SFWMD 2014). This concept recognizes that significant harm may happen naturally, at a frequency associated with the occurrence of a particular level of drought.

Most approaches to establishing freshwater inflow requirements are ultimately resource based by quantifying the relationships between freshwater inflow, estuarine conditions, and biological resources (Chamberlain and Doering 1998b, Alber 2002, Palmer et al. 2011). The freshwater requirements of estuarine fisheries are often included in the planning, allocation, and management of water resources (Robins et al. 2005). The fisheries themselves can be economically important. Their dependence on freshwater inflow is comprehensible to a wide variety of stakeholders (Alber 2002) and illustrates both the ecological and economic importance of freshwater supplies to estuaries (Copeland 1966).

In this component, we established quantitative relationships between hydrologic variables (rainfall and freshwater inflow) and commercial blue crab landings in Lee County, Florida. Secondly, we related reductions in catch to recovery time under average hydrologic conditions. Lastly, we analyzed periodicity in the time series of hydrologic and crab catch data to investigate return frequency.

The blue crab is an estuarine dependent macroinvertebrate that supports valuable recreational and commercial fisheries along the Atlantic and Gulf coasts (Guillory 2000, Mazzotti et al. 2006, Murphy et al. 2007). Blue crab, common in the crab trap fishery in the CRE, has historically had large and consistent landings within the estuary (Mazotti et al. 2006). It is classified as "highly abundant" by NOAA's Estuarine Living Marine Resources program (Nelson 1992). In 2003, licensed crab fishers in Lee County numbered 183 and the number of licensed crab traps was over 63,000 (FWRI 2003). This fishery expends a large effort and yields large numbers of crabs for local and distant consumers while supporting a valuable local economic employment opportunity.

Methods

Study Area

The CRE, a portion of the C-43 Canal (upstream of S-79), and Lee County are located on the southwest coast of Florida (**Figure A-58**). The C-43 Canal runs 67 km from Lake Okeechobee to the Franklin Lock and Dam (S-79). S-79 separates the fresh water from the CRE, which terminates 42 km further downstream at Shell Point. The system has been altered to provide for navigation, water supply, and flood control on both a local and regional scale (Chamberlain and Doering 1998a, Doering et al. 2006). The river has been straightened and deepened and three water control structures (S-77, S-78 and S-79) have been added (Antonini et al. 2002). The Franklin Lock and Dam (S-79) was added in part to act as a salinity barrier at the head of the estuary (Flaig and Capece 1998). The historic river (now the C-43 Canal) has also been artificially connected to Lake Okeechobee to convey releases of water to tide for the purpose of regulating water levels in the lake. The estuarine portion of the system has also been modified: a navigation channel has been dredged (Antonini et al. 2002) and a causeway has been built across the mouth of San Carlos Bay.

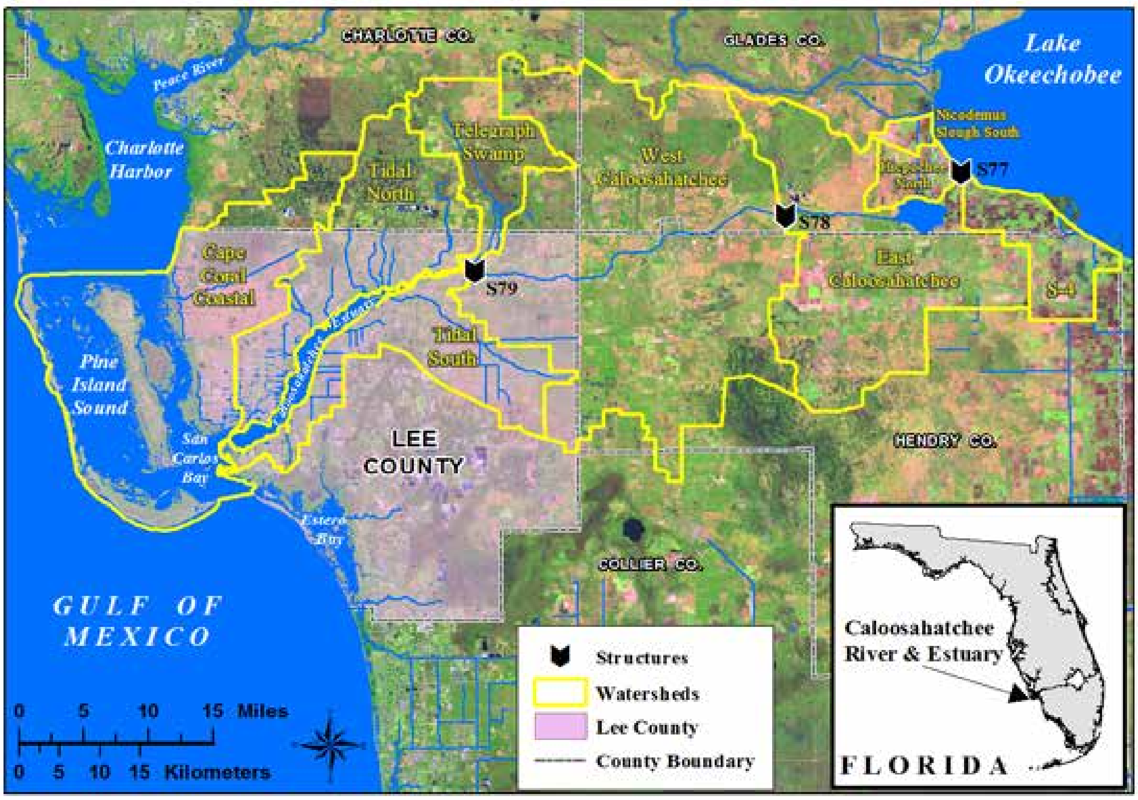


Figure A-58. Location of Lee County and the Caloosahatchee River and CRE. Over 60% of land area in Lee County drains into the CRE and San Carlos Bay.

Inflow Characteristics

Major surface water inflows to the estuary come from Lake Okeechobee, the C-43 Basin upstream of S-79 (S-4 Basin, and East and West Caloosahatchee subbasins) and the Tidal Basin (i.e. the Telegraph Swamp, Tidal North, and Tidal South subbasins) located between S-79 and Shell point (**Figure A-58**). Over the long term (1997–2014), the annual total surface water inflow from these three sources averages 1.8 x 10^6 ac-ft with 31.6% coming from Lake Okeechobee, 47.6% from the Caloosahatchee Basin, and 21% from the Tidal Basin (Buzzelli et al. 2015a).

Data Sources

Monthly landings of blue crabs in Lee County for the period of November 1984 through December 2013 were obtained from the Florida Fish and Wildlife Conservation Commission’s Florida Wildlife Research Institute in St. Petersburg, Florida (**Figure A-59**). Fisherman are asked to report the weight of hard and soft shell crabs caught and the number of traps pulled on a per trip basis. The number of traps pulled is not always reported and is estimated when missing (Murphy et al. 2007). Daily rainfall (inches) for Lee County and daily discharge (cfs) at S-79 were obtained from SFWMD’s DBHYDRO (www.sfwmd.gov/science-data/dbhydro). Inflows from the Tidal Basin were predicted using a rainfall-runoff model calibrated to five years of measured discharge data from tidal creeks (Wan and Konya 2015). Total discharge to the estuary was taken as the sum of discharge at S-79 and inflows from the Tidal Basin.

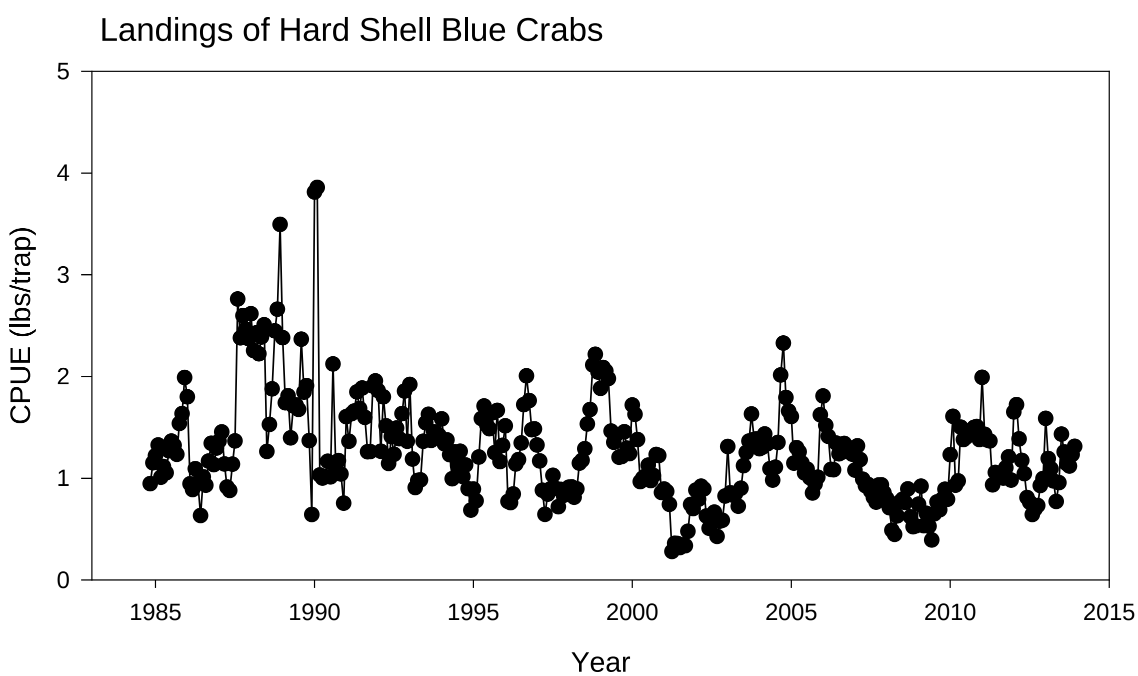


Figure A-59. Monthly landings of hard shell blue crabs in Lee County Florida. (Notes: Data from the Florida Fish and Wildlife Conservation Commission’s Florida Wildlife Research Institute. lbs/trap – pounds per trap.)

Relationships between Hydrologic Variables and Blue Crab Catch

All time series were expressed in terms of water years. For example, the water year 1998 began on May 1, 1997, and ended April 30, 1998. The advantage of defining the time series on the basis of water year is that each 12-month period contains one full wet season (May–October) and one full dry season (November–April). The POR for analysis was 28 years (WY1986–WY2013). Monthly landings of crabs (pounds [lbs] hard, lbs soft) and measures of fishing effort (number of trips and number of traps pulled) were summed to produce annual totals. From these, annual estimates of CPUE were computed. CPUE was defined as lbs of crab (hard or soft) per trap (e.g. lbs of hard shell crabs per total number of traps pulled). Rainfall in Lee County, discharge at S-79, and total discharge (Tidal Basin + S-79) were also expressed on both an annual and seasonal (dry and wet) basis. To allow for examining the effects of previous years of rainfall and discharge on a current year's CPUE, the POR for hydrologic variables ran from WY1981 to WY2013.

Statistical Analyses

Statistical analyses were conducted using SAS version 9.3. Following Wilber (1994), annual estimates of CPUE for hard and soft shelled crabs were tested for association with rainfall in Lee County and discharge (at S-79 and total discharge) at annual lags of zero to five years by calculating the Pearson Correlation coefficient. A lag of 0 indicates that the current year's CPUE was paired with the current year's rainfall or discharge. At a lag of 1, CPUE was correlated with the previous water year's rainfall or discharge.

When a correlation using unadjusted data was statistically significant, each time series involved was tested for a long-term trend (linear increase or decrease over time) using least squares linear regression. If significant, a de-trended time series was obtained from the residuals of the least squares regression of CPUE on rainfall or flow. This procedure yielded a time series of deviations from the long-term mean (de-trended residuals). The time series were also tested for autocorrelation at a lag of one year. If statistically significant, autocorrelation was removed by subtracting the previous year's value from the value of a variable for a given year. Correlations between CPUE and hydrologic factors were reevaluated using the corrected time series.

Relationships between CPUE and hydrologic factors (rainfall and discharge) were quantified using a geometric mean functional regression (Ricker 1973), which provides an estimate of central tendency. This approach is appropriate when there is error in both X and Y. In order to evaluate periodicity, a spectral analysis (Proc Spectral in SAS) was conducted. Following Chatfield (1989), any trend (monotonic increase or decrease over time) was removed before analysis using least squares linear regression.

Loss of Water Resource Function and Recovery in Relation to Rainfall

In order to estimate the rate of recovery of CPUE, we developed a relationship between magnitude of the loss of resource function and recovery time. In the case of the blue crab fishery, the water resource function was expressed as CPUE. Loss of resource function was therefore a decrease in CPUE. In quantifying the relationship between loss of resource function and recovery time, three assumptions were made: (1) loss of resource function occurred when CPUE fell below the long-term annual mean of 1.26 pounds per trap (lbs/trap) (2) recovery occurred under average hydrologic conditions; and, (3) recovery was achieved when CPUE returned to the long-term annual mean.

To determine rate of recovery, instances from the POR (WY1986–WY2013) in which CPUE increased from one year to the next were extracted, expressed as an annual rate of increase in

CPUE, and regressed on rainfall occurring during the first of the two years. This relationship was then used to estimate the change in CPUE associated with one year of average rainfall.

The loss in resource function or deviation from the long-term mean that can be recovered in one year was the estimated change in CPUE associated with one year of average rainfall. The loss that can be recovered in two years was twice the change in CPUE associated with one year of average rainfall, and so on.

The actual value of the CPUE that takes one year to recover to the long-term mean was the long-term mean minus the change in CPUE associated with one year of average rainfall. For a two-year recovery, the value of the CPUE was the long-term mean minus twice the change in CPUE associated with one year of average rainfall.

The above analysis of the rainfall associated with loss of blue crab CPUE and recovery was, to a certain extent, limited by the quantity of data within the POR. The time series did not include a sufficient number of events to quantify these relationships simply by examining the record itself. As an alternative, we conducted Monte Carlo simulations, to acquire the frequency or probability of rainfall associated with CPUE recovery times of two and three years. Monte Carlo simulations have been used widely in fishery and hydrological research for assessing a model's outputs with different types and levels of variability or uncertainty in the model's inputs (e.g. Restrepo et al. 1992, Punt 2003, and Petrie and Brunsell 2011). In order to conduct a Monte Carlo simulation, an underlying probability distribution was specified. A normality test (Shapiro-Wilk's test [W] along with the normal quantile plot) of the Lee County dry season rainfall data from 1965 to 2013 indicated that the variability of the dry season rainfall can be well described by a log-normal distribution (**Figure A-60**; $W = 0.98$, $p = 0.752$, and significance $[\alpha] = 0.05$). Monte Carlo simulations were conducted based on this dry season rainfall probability distribution to generate ten sets of 10,000 years of dry season rainfall.

The functional regression equation relating annual CPUE and Lee County rainfall was used to predict blue crab CPUE with the generated rainfall data as inputs. The years with CPUE lower than the long-term (WY1986–WY2013) mean CPUE followed by successive two or three years of recovery back to normal were identified, respectively. The average dry season rainfall for these years and associated average return interval and probability of occurrence at least once in ten years were calculated.

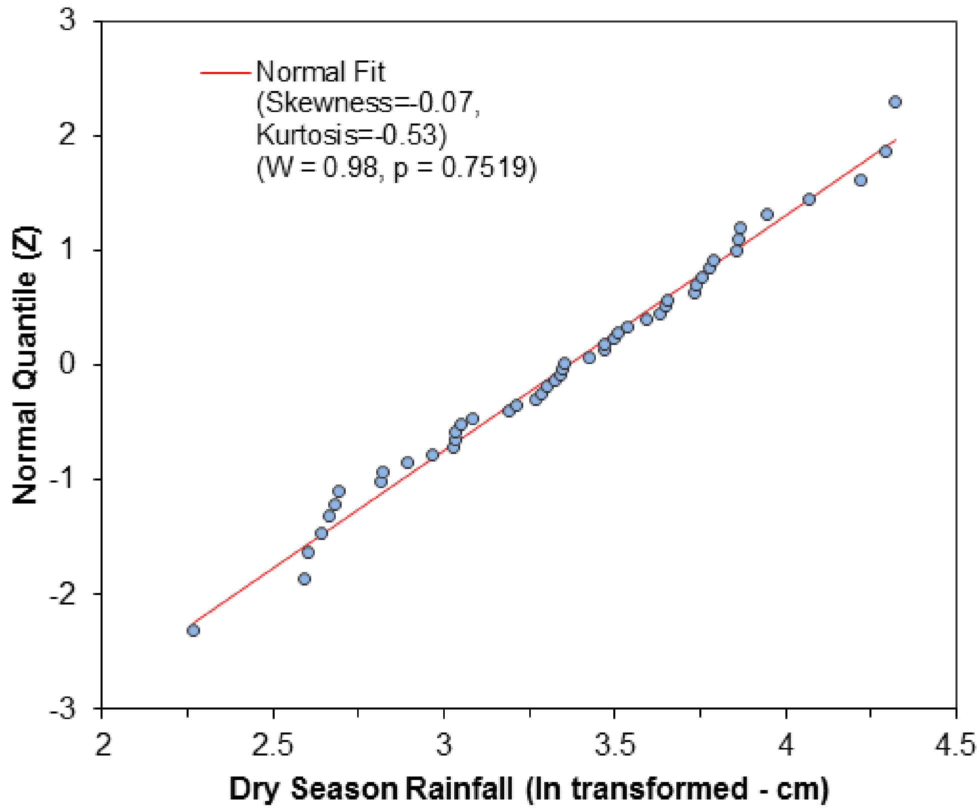


Figure A-60. Normality test of natural log-transformed dry season rainfall during WY1966–WY2013. (Note: cm – centimeters.)

Determination of Flow Associated with Rainfall

To convert estimates of rainfall associated with various recovery times to discharge (S-79 or total), regression analysis was performed. To maximize the probability of detecting a statistically significant relationship between discharge and rainfall, a longer POR (WY1967–WY2013) was used in this analysis.

Results

Relationships between Hydrologic Variables and Blue Crab Catch

Annual rainfall in Lee County averaged about 55 inches and ranged from a low of 41 inches in WY1981 to a high of 81.5 inches in WY1983. About 76% of the total annual rainfall occurred in the wet season and 24% in the dry season (**Table A-33**). Dry season rainfall ranged from a low of 3.8 inches in WY2009 to a high of 29.6 inches in WY1998 (**Figure 61A**). Annual discharge at S-79 averaged 1,764 cfs (**Table A-33**) ranging from a low of 113 cfs in WY2008 to a high of 5,044 cfs in WY2006. Daily average discharge at S-79 during the wet season (2,294 cfs) was nearly twice the average dry season discharge (1,238 cfs). Dry season discharge at S-79 ranged from a low of 52 cfs in WY2008 to a high of 5,616 cfs in WY1998. Total discharge averaged 2,267 cfs on an annual basis with Tidal Basin inflows adding about 500 cfs to the discharge at S-79. Daily total discharge averaged 3,055 cfs in the wet season and 1,480 cfs in the dry season, with Tidal Basin inflows contributing 760 and 245 cfs in the wet and dry seasons, respectively (**Table A-33**).

Table A-33. Annual and seasonal (wet versus dry) rainfall (inches) in Lee County and discharge (cfs) at the Franklin Lock and Dam (S-79) and total discharge to the estuary (sum of S-79 and Tidal Basin). (Notes: Values are average [standard deviation]. POR was WY1981–WY2013.)

	Annual	Wet Season	Dry Season
Lee County Rainfall	55.2 (9.2)	42.3 (7.7)	12.8(5.9)
Discharge at S-79	1,764 (1208)	2,294 (1413)	1,235 (1445)
Total Discharge	2,267(1332)	3,055(1586)	1,480 (1599)

Annual landings in Lee County were dominated by hard shelled crabs with soft shelled crabs averaging only 3% of the total catch in lbs (**Table A-34**). The CPUE for hard shelled crabs was also higher than for soft shelled crabs. On an annual basis, CPUE for hard shelled crabs averaged 1.26 lb/trap and ranged from a high of 2.1 lb/trap in 1989 to a low of 0.70 lb/trap in 2002 (**Figure A-61B**). For soft shelled crabs, CPUE averaged 0.75 lb/trap (**Table A-34**), ranging from a high of 1.58 lb/trap in 1989 to a low of 0.05 lb/trap in 2004.

Table A-34. Mean annual landings in pounds per year (lbs/yr) of hard and soft shell blue crabs for WY1986–WY2013. (Note: Values are average [standard deviation].)

	Landings lbs/yr	CPUE lbs/trap
Hard Shell	1,315,808 (711,508)	1.26 (0.35)
Soft Shell	36,515 (38,465)	0.75 (0.43)

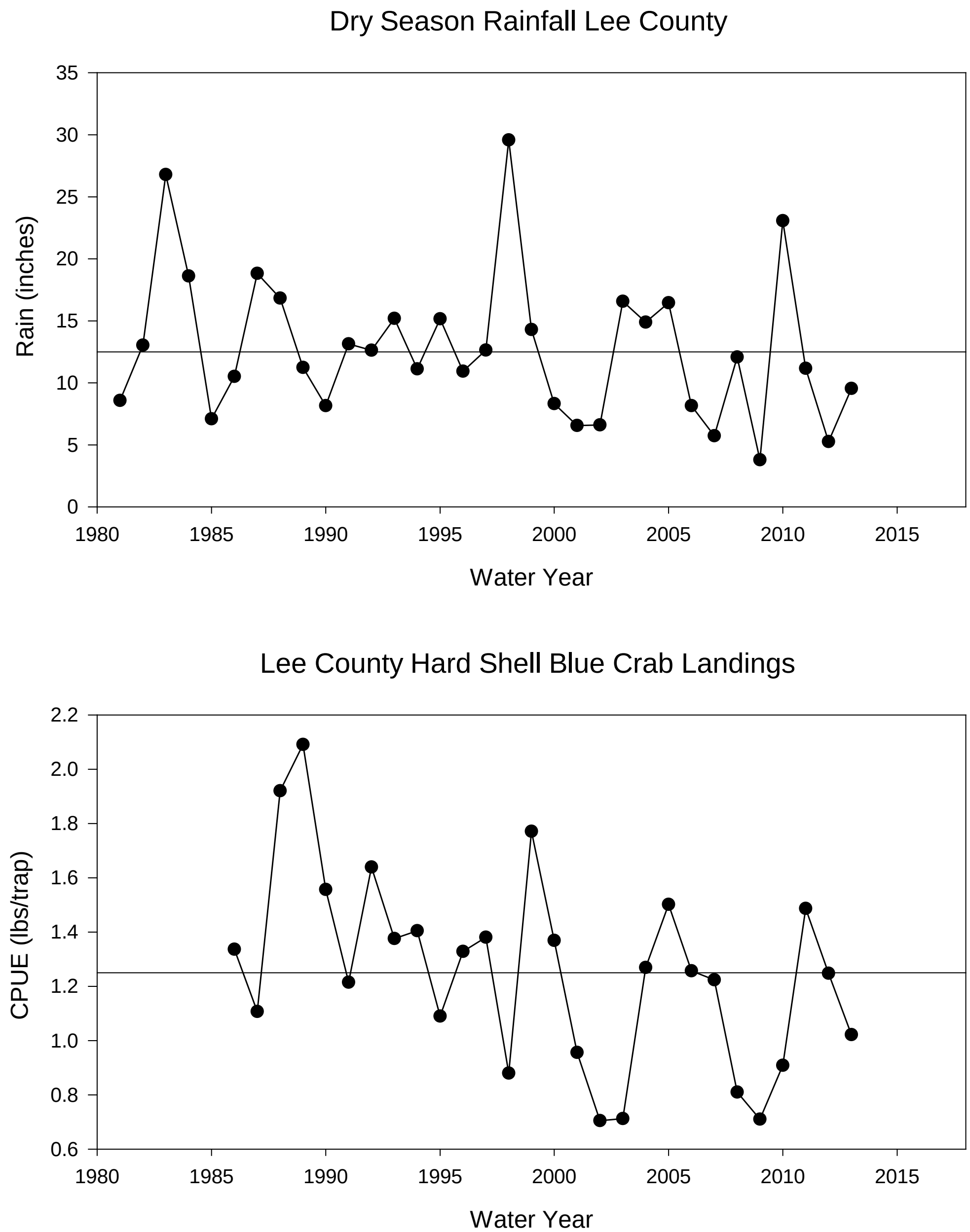


Figure A-61. (A) Dry season (November–April) rainfall in Lee County. (B) Annual landings of hard shell blue crabs.

CPUE for hard and soft shelled crabs were tested for association with rainfall and discharge (S-79 and total) at annual lags of 0 to 5 years. Statistically significant ($p < 0.05$) correlations between CPUE and rainfall or discharge were found only when hydrologic variables were lagged by one year. Further, only correlations with dry season rainfall or discharge, lagged by one year, were statistically significant (**Table A-35**). Therefore, the CPUE during the current year was positively associated with rainfall or discharge during the previous year's dry season. Of the three hydrologic variables tested, dry season rainfall explained the most variance in CPUE. A linear functional regression indicated that dry season rainfall explained about 45% of the variability in CPUE of hard shelled crabs, with CPUE increasing at a rate of 0.063 lbs/trap per inch (lbs/trap/inch) of rain (**Figure A-62**). The 95% confidence interval (Ricker 1975) for the slope was 0.046 to 0.084 lbs/trap/inch of rain.

Table A-35. Correlation of unadjusted hydrologic variables with unadjusted estimates of CPUE. (Notes: n = 28 in all cases. Statistical significance: * p < 0.10, ** p < 0.05, and ***p < 0.01.)

Variable	Annual CPUE	
	Hard (lbs/trap)	Soft (lbs/trap)
Lee County Rainfall		
Water Year (Lag 1)	0.216	-0.085
Wet Season (Lag 1)	-0.251	-0.309
Dry Season (Lag 1)	0.673***	0.399**
Discharge at S-79		
Mean Water Year (Lag 1)	0.289	0.091
Mean Wet Season (Lag 1)	0.083	-0.161
Mean Dry Season (Lag 1)	0.424**	0.345*
Total Discharge = S-79 + Tidal Basin		
Mean Water Year (Lag 1)	0.293	0.094
Mean Wet Season (Lag 1)	0.058	-0.177
Mean Dry Season (Lag 1)	0.450**	0.369*

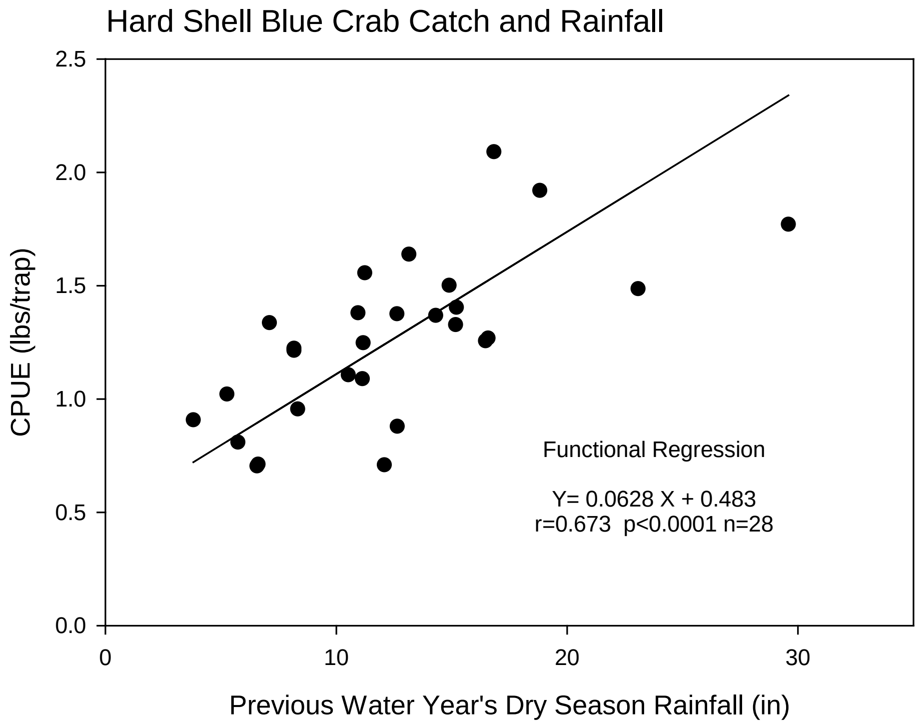


Figure A-62. Functional regression of hard shell blue crab landings on the previous year's dry season rainfall (unadjusted data).

Long-term trend and autocorrelation may lead to spurious correlations between two time series (Chatfield 1989). For example, two variables that are both decreasing over time may appear correlated even though decreasing trends may have different causes. Linear regressions of dry season rainfall, total discharge and discharge at S-79 on water year were not statistically significant indicating that these time series showed no long-term trends. CPUE for both hard and soft shelled crabs exhibited significant, declining trends over time. Only CPUE for soft shelled crabs had significant autocorrelation at a lag of one year. In other words, for this variable, the current year's CPUE appeared dependent on the previous year's CPUE. When corrections for long-term trend and autocorrelation at lag 1 were made as appropriate, CPUE for both hard and soft shelled crabs were still correlated with dry season rainfall or discharge at a lag of 1 year (**Table A-36**). Because soft-shelled crabs accounted for a small percentage of the total catch and because correlations between discharge and CPUE were relatively weak, further analysis focused on hard-shelled crabs and dry season rainfall.

Table A-36. Correlations between hydrologic variables and CPUE after adjustment for long-term trend (de-trended) and autocorrelation (corrected) as appropriate. (Notes: Included are correlations lagged by one year for dry season [November–May] Lee County rainfall, freshwater discharge through S-79, and total discharge calculated as the sum of S-79 and the Tidal Basin. Statistical significance: * p < 0.10, ** p < 0.05, and *** p < 0.01.)

Variable	Annual CPUE	
	Hard (lbs/trap) (de-trended)	**Soft (lbs/trap) (de-trended corrected)**
Lee County Rainfall		
Dry Season (Lag 1)	0.696 ***	0.495***
Discharge at S-79		
Mean Dry Season (Lag 1)	0.468 **	0.426**
Total Discharge = S-79 + Tidal Basin		
Mean Dry Season (Lag 1)	0.497***	0.447**

Loss of Water Resource Function and Recovery in Relation to Rainfall

Year-to-year increases in unadjusted (not de-trended) CPUE for hard shelled crabs (n = 12) over the period WY1986–WY2013 were expressed as an annual rate of increase in CPUE and associated with dry season rainfall occurring in the first of the two years (**Figure A-63**). The functional regression of annual rate of increase in CPUE on dry season rainfall was statistically significant (**Figure A-63**, $p < 0.005$, $R^2 = 0.570$). For the average dry season rainfall (WY1986–WY2013) of 12.45 inches per year, this relationship yielded an annual increase of 0.22 CPUE per year. The deviation from the long-term mean that would be recovered after one year of average rainfall was therefore 0.22 CPUE. For two and three year recoveries, the deviations were 0.44 CPUE and 0.66 CPUE, respectively (**Table A-37**). Given a long-term (WY1986–WY2013) average of 1.26 CPUE, the actual CPUE associated with a one-, two-, or three-year recovery are given in **Table A-37**. Using the equation in **Table A-35**, the previous year's dry season rainfall associated with these CPUEs was calculated. The rainfall corresponding to recoveries of one to three years ranged from 8.9 inches (1 year) to 1.9 inches (3 years).

With the Monte Carlo analysis, recovery periods of two and three years back to the average CPUE (1.26 lb/trap) were considered to estimate the dry season rainfall associated with each. Results, summarized in **Table A-36**, were based on about 750 observations of recoveries requiring two to three years in each of the ten Monte Carlo runs. Average dry season rainfall associated with a deviation below the long-term average CPUE that took two years to recover was 7.1 inches. The average dry season rainfall associated with a deviation requiring three years to recover was 6.4 inches (**Table A-36**).

It is important to note that lagged (by 1 year) total dry season discharge and lagged dry season discharge at S-79 were also significantly related to CPUE for hard shelled crabs (

Table A-36). However, neither of these variables was related to year-to-year increases in CPUE as was the case for dry season rainfall (**Figure A-63**). Thus, a parallel analysis employing flow instead of rainfall could not be accomplished. Both flow variables were related to dry season rainfall in the current year. The data could be described by non-linear, exponential relationships that explained more than 60% of the variance (**Figure A-64**).

The exponential relationships were used to convert the estimates of dry season rainfall to inflow. The average daily dry season discharge at S-79 associated with one-, two-, or three-year recoveries ranged from 239 to 543 cfs (**Table A-37**). Accounting for additional inflow from the Tidal Basin resulted in flows ranging from 304 to 675 cfs (**Table A-37**).

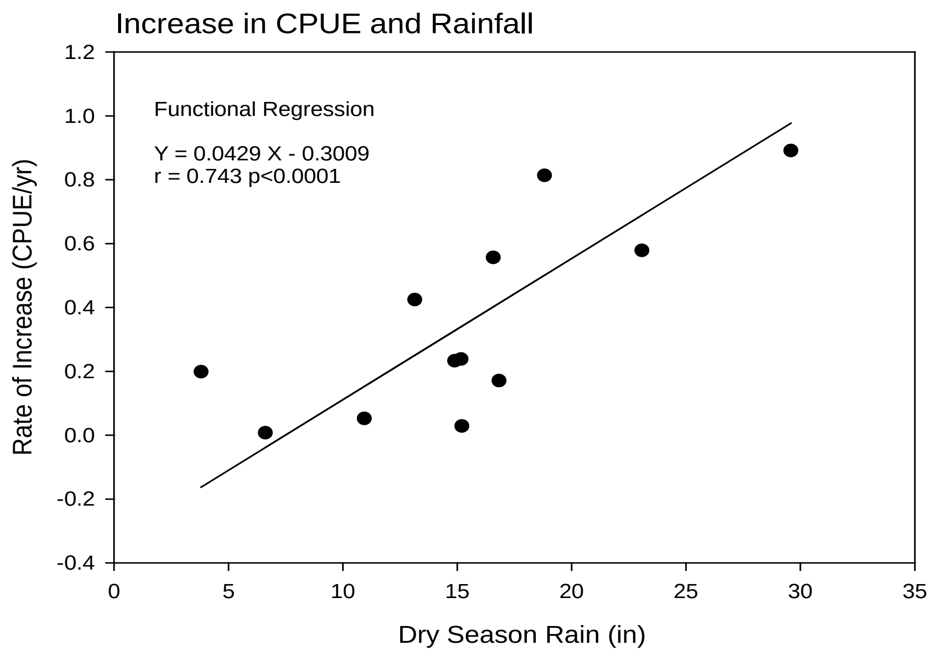


Figure A-63. Functional regression of the increase in CPUE from one year to the next on the dry season rainfall occurring during the first of the two years. (Note: Data from **Figure A-61**.)

Table A-37. Estimates of the preceding water year's dry season rainfall (Lee County) that produce annual catches of hard shelled crabs that will return to the long-term mean CPUE (1.26 lbs/trap) after one to three years of average dry season rainfall (12.45 inches). (Notes: Estimates were made using a regression technique and a probabilistic Monte Carlo approach. Also given are the dry season discharge at S-79 and total discharge [S-79 + Tidal Basin] associated with the dry season rainfall in Lee County.)

Method	Rainfall (inches)	CPUE (lbs/trap)	Years to Recover	Discharge S-79 (cfs)	Discharge Total (cfs)
Regression	8.9	1.04	1	543	675
	5.4	0.82	2	360	453
	1.9	0.66	3	239	304
Monte Carlo	7.1	0.97	2	440	552
	6.4	0.93	3	407	512

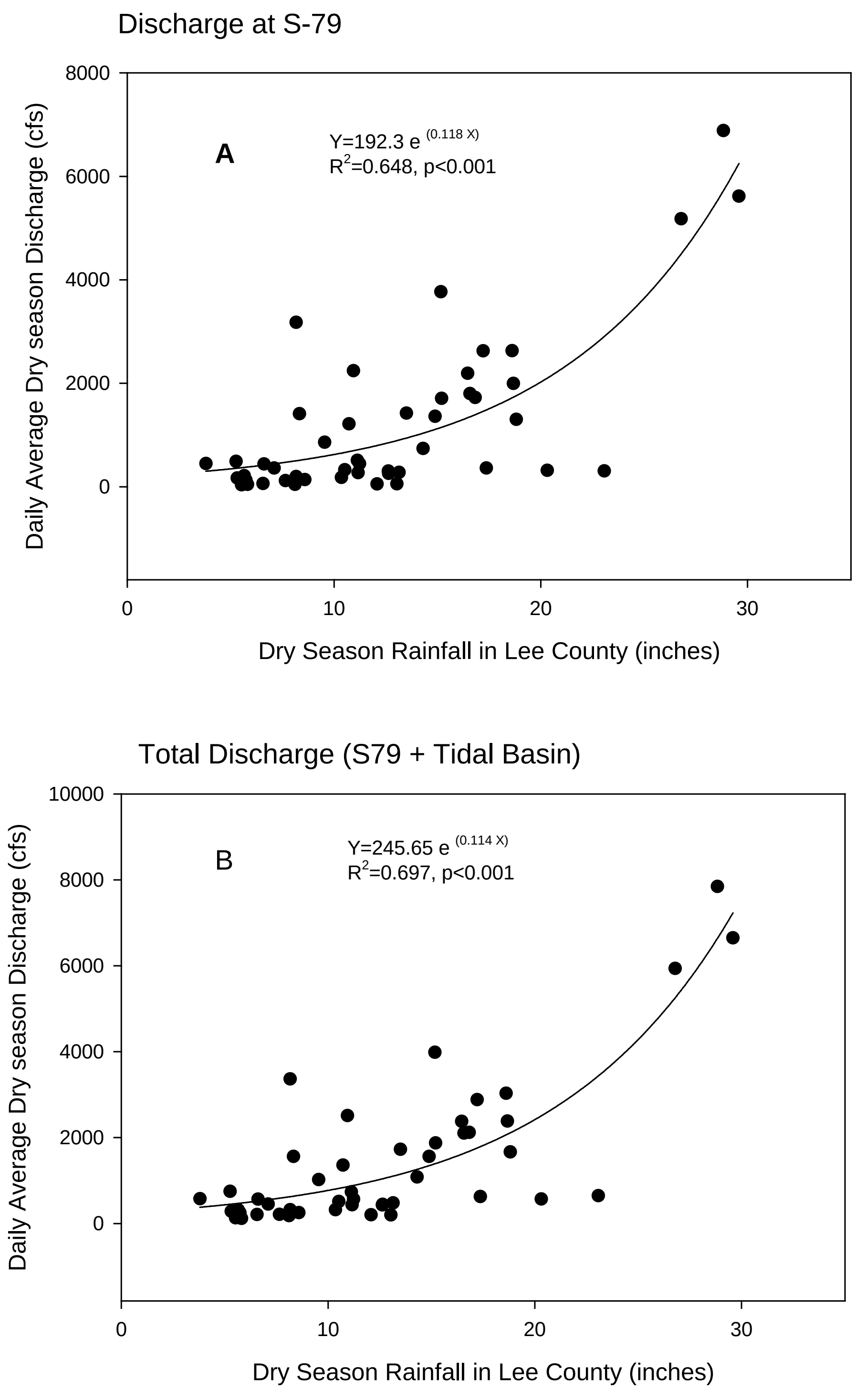


Figure A-64. Exponential relationships between dry season rainfall in Lee County and discharge to the CRE at S-79 (top panel) or total discharge (bottom panel).

Return Frequency

Results of the spectral analysis indicated that both dry season rainfall and CPUE showed statistically significant fluctuations with a period of 5.6 years (**Figure A-65**). Analysis of the results of the Monte Carlo simulations indicated that the average rainfall with a two-year recovery of 7.1 inches has a return interval of 5.8 years, very close to the results of the spectral analysis (**Table A-38**). The average rainfall with a three-year recovery was 6.4 inches with a return interval of 8.2 years (**Table A-38**). The probability for such dry season rainfall < 6.4 inches to occur at least once in ten years is still high (73%).

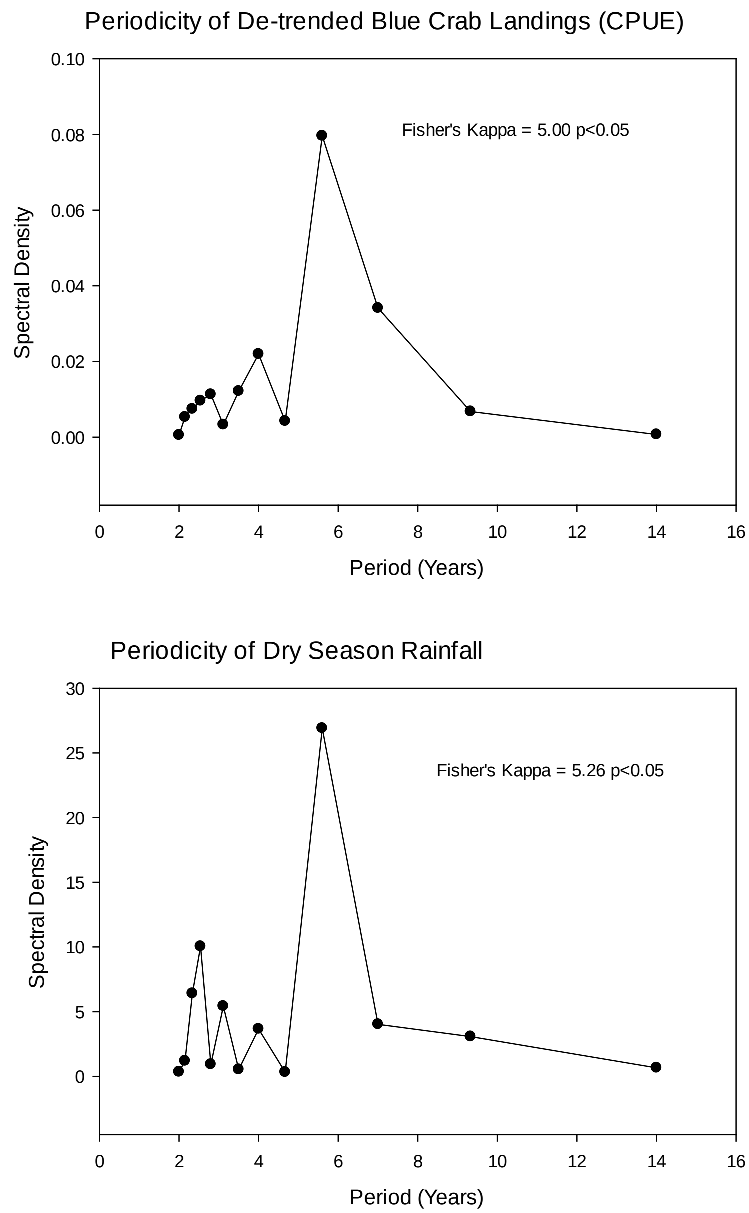


Figure A-65. Results of spectral analysis. Periodicity of de-trended blue crab landings (top panel) and dry season rainfall (bottom panel) in Lee County for WY1986–WY2013. (Note: Results indicate that both time series show major fluctuation with a period of about six years.)

Table A-38. Average dry season rainfall for potential significant harm and associated return interval and probability of occurrences from Monte Carlo simulations.

Simulation	1	2	3	4	5	6	7	8	9	10	Mean
Dry Season Rainfall with 2-year Recovery (inches)	7.1	7.1	7.1	7.1	7.2	7.2	7.1	7.1	7.1	7.0	7.1
Average Return Interval (year)	5.8	5.5	5.9	5.8	5.7	5.5	6.0	5.9	5.8	6.0	5.8
Probability of 1-in-10 Year Occurrence (%)	85	87	84	85	86	87	84	85	85	84	85
Dry Season Rainfall with 3-year Recovery (inches)	6.4	6.1	6.2	6.7	6.6	6.5	6.0	6.5	6.5	6.4	6.4
Average Return Interval (years)	8.3	9	9.4	7.4	7.6	7.7	8.9	7.9	7.9	8.2	8.2
Probability of One in Ten Years Occurrence (%)	72	69	68	77	76	75	70	74	74	73	73

Discussion

The blue crab is an estuarine dependent species that utilizes the full range of salinity from oligohaline conditions to > 30 during its life time (Perry and McIlwain 1986, Longley et al. 1994). Salinities > 20 are required for successful reproduction and larval development (Sandoz and Rogers 1944, Perry and McIlwain 1986). Juveniles may use low salinity (< 15) regions of estuaries as nurseries (Van Engel 1958, Posey et al. 2005). During a three-year monitoring program in the CRE, Stevens et al (2008) observed recruitment of juvenile crabs (< 40 millimeter carapace width) primarily between November and April, with highest numbers in February, March, and April. Most of these were caught in low salinity conditions (0.5 to 5). There is also partitioning of the estuarine salinity gradient according to sex, with adult males remaining in low salinity waters, while mature females prefer the higher salinities found in lower estuarine and coastal regions (Perry and McIlwain 1986).

Given the dependence on a wide range of salinity for successful completion of its life cycle, it is not surprising that the productivity of blue crabs in an estuary may be influenced by freshwater inflow. Lower abundances of blue crabs have been associated with drought conditions in South Carolina (Childress 2010) and several Texas estuaries (Palmer et al. 2011). Commercial landings provide a convenient measure of productivity (Wilber 1994). Results from this study agreed with previous investigations that have reported positive relationships between freshwater inflow and landings of blue crabs (Meeter et al. 1979, Rogers et al. 1990, Wilber 1994, Guillory 2000). Wilber (1994) suggested three possible explanations for such relationships: (1) increased fresh water will reduce estuarine salinity and provide more low salinity habitat for juvenile crabs; (2) increased flows may further broadcast cues that may attract females from offshore, thus increasing the brood stock; and (3) higher inflows increase nutrient and detrital loading and thus directly or indirectly enhance food supply.

The long-term and interannual patterns that we observed for Lee County landings agree well with those observed statewide in Florida. In their recent assessment of the blue crab fishery in Florida, Murphy et al (2007) characterized the fishery as follows:

> Commercial landings in Florida have shown a general decreasing trend since the mid 1980's. Superimposed on this pattern are large oscillations often related to extended years of drought when blue crab production is apparently low and wet years when blue crab production is apparently high.

The POR analyzed here (WY1986–WY2013) exhibited a decreasing long-term trend with much of the interannual variability (45%) explained by rainfall. The lower the rainfall and inflow during the dry season, the lower the following year's production of blue crabs. A similar lagged relationship between annual crab landings and the previous year's inflow from the Apalachicola River was observed by Wilber (1994). Blue crabs in the Gulf of Mexico reach harvestable size within a year of age (Perry 1984 as cited in Wilber 1994). The positive correlations between crab landings and river flows lagged by one year may reflect a positive influence of fresh water on juvenile crabs that reach harvestable size the following year (Wilber 1994). In this study, current annual landings were correlated with the previous year's dry season rainfall and inflow. The recruitment of juvenile blue crabs during the dry season (November–April) in the CRE may explain this correlation (Stevens et al. 2008).

Two key relationships are required to establish resource protection criteria: relationships between (1) changes in hydrology and changes in water resource function and (2) the magnitude of the functional loss and time to recover. In this component we have established a relationship between CPUE, which is the resource function, and dry season rainfall during the preceding water year, which represents the hydrology of the system. Since rainfall and freshwater flow were also related, changes in CPUE can also be related to a flow variable (e.g. discharge at S-79 and total discharge). We have also related the loss of water resource function to recovery time. Functional loss is defined as a negative deviation from the long-term mean CPUE. Recovery is achieved when the CPUE returns to the long-term mean. We have identified the CPUE that should recover to the long-term mean with one, two, or three years of average rainfall. Lastly, we have examined return frequency using spectral analysis and a Monte Carlo analysis.

Component Study 11: Relationships between Freshwater Inflow, Salinity, and Potential Habitat for Sawfish (*Pristis pectinata*) in the CRE

Christopher Buzzelli, Peter Doering, Yongshan Wan, and Detong Sun

Abstract

The smalltooth sawfish is an endangered species that historically ranged from Texas to North Carolina. The distribution and abundance of sawfish have declined due to overfishing and habitat loss. Presently, the CRE is an important sawfish nursery. Juvenile sawfish habitat can be characterized as nearshore environments < 1 m in depth, where salinities range from 12 to 27. This study quantified sawfish habitat with variable inflow to the CRE in the dry season using a combination of bathymetric analyses and hydrodynamic modeling. Inflows of 150–300 cfs positioned the 12 and 27 salinities in the shallowest part of the estuary (10 to 30 km downstream). Specifically, the area of sawfish habitat was greatest (5.7 km^2) when inflow through the S-79 structure was 270 cfs in the dry season. Under reduced inflow, the habitat migrated into the channel above Beautiful Island where it was compressed against S-79. Higher inflows pushed the position of salinity of 27 (S_{27}) out of the estuary.

Introduction

Fluctuations in freshwater inflows over time scales ranging from weeks to years have altered salinity regimes and impacted the ecological integrity of the CRE (Chamberlain and Doering 1998a, Barnes 2005). Changes in freshwater inflows and salinity have been shown to affect the distribution and dynamics of many taxa and communities including phytoplankton and zooplankton (Tolley et al. 2010, Radabaugh and Peebles 2012), SAV (Doering et al. 2001, 2002, Lauer et al. 2011), oysters and their pathogens (La Peyre et al. 2003, Barnes et al. 2007, Volety et al. 2009), fauna inhabiting oyster reefs (Tolley et al. 2005, 2006), and fishes (Collins et al. 2008, Heupel and Simpfendorfer 2008, Stevens et al. 2010, Simpfendorfer et al. 2011, Poulakis et al. 2013).

The balance between downstream transport of fresh water and the upstream encroachment of salinity creates gradients that influence all biogeochemical and biological processes and patterns. The gradient can be represented by lines of equal salinity (e.g. isohalines) whose positions fluctuate up and down the estuary with freshwater inflow(s), tidal cycles, and meteorological phenomena (e.g. fronts, winds, and storms). Particular isohalines provide indications of desirable (or undesirable) salinity conditions for sentinel organisms or communities (Jassby et al. 1995).

The smalltooth sawfish (*Pristis pectinata*) is an endangered species that historically ranged from Texas to North Carolina in the eastern United States (Simpfendorfer et al. 2011, Norton et al. 2012). The distribution and abundance of sawfish have declined due to overfishing and widespread habitat loss. The patterns of decline in the largetooth sawfish (*P. Pristis*) are similar to smalltooth sawfish (Fernandez-Carvalho et al. 2014). Presently, sawfish populations are limited to habitats in Southwest Florida from Charlotte Harbor to the Dry Tortugas, including the CRE (NOAA 2009).

Little was known about sawfish feeding, reproduction, or habitat usage prior to designation as an endangered species in 2003 (Norton et al. 2012). More recently the CRE has been recognized as an essential nursery for neonates and juvenile sawfish (Simpfendorfer et al. 2011, Carlson et al.

2014). A suite of research studies was conducted to examine the distribution, location, and activity of juvenile sawfish in southwestern Florida and improve the existing understanding of the relationships between population dynamics, environmental conditions, and management actions (Poulakis et al. 2014).

Sawfish, cownose rays (*Rhinoptera bonasus*), and bull sharks (*Carcharkinus leucas*) are important components of the elasmobranch community in the CRE (Collins et al. 2008, Ortega et al. 2009, Heupel et al. 2010, Poulakis et al. 2011). Like many estuarine organisms, salinity is a key driver for these fish populations (Jassby et al. 1995, Collins et al. 2008, Heupel and Simpfendorfer 2008, Ortega et al. 2009). Migration within the estuary is modulated through a combination of osmotic regulation and the availability of prey resources (Poulakis et al. 2013). Individual cownose rays followed their preferred salinity range further upstream with decreasing freshwater discharge (Collins et al. 2008). A similar situation exists for bull sharks, which utilize the CRE as a nursery for at least 18 months, prefer salinities of 7 to 20, and move upstream with reduced inflow (Heupel and Simpfendorfer 2008).

Smalltooth sawfish generally prefer salinities of 12 to 27 but can survive and grow over a wider range (Poulakis et al. 2013). The desirable habitat for sawfish has been described as adjacent to red mangroves where nearshore depths are £ 0.9 m (Poulakis et al. 2011, Norton et al. 2012, Carlson et al. 2014). Sawfish spend their first few years of life in the CRE. Recent studies have shown that small sawfish (< 1 m) grow very fast over the full range of salinity conditions. While medium-sized fish (< 1.5 m) respond to changes in salinity lagged on a 90-day time scale, the largest fish (> 1.5 m) with the widest home range are more likely to be influenced by prey availability (Poulakis et al. 2013). Additionally, the average daily activity space (0 to 4 km) is correlated to sawfish body length (60 to 260 centimeters) as larger individuals can tolerate greater variations in salinity (Carlson et al. 2014).

Similar to cownose rays and bull sharks, increased salinity promotes upstream migration of juvenile sawfish away from downstream hot spots (Poulakis et al. 2013). Whereas juvenile sawfish can be found throughout the CRE, there are documented hotspots for smalltooth sawfish: Iona Cove, Glover Bight, the Cape Coral Causeway, and the US 41 Bridges near Fort Myers (Poulakis et al. 2014). Many sawfish are located in the lower estuary (Iona Cove and Glover Bight) when salinity is favorable, but migrate further upstream (US 41 Bridges) as salinity increases. This is potentially problematic for two reasons. First, the upper CRE from S-79 to Beautiful Island is much deeper and narrower with greatly reduced nearshore shallow habitat. Second, upstream migration into a bathymetrically compressed habitat potentially places juvenile sawfish in closer proximity to larger predators such as bull sharks (Poulakis et al. 2011).

It is possible that environmental factors other than salinity (i.e., temperature, DO, depth, shoreline attributes, and food availability) influence the distribution of juvenile sawfish (Poulakis et al. 2014). Although the endangered status of sawfish inhibits traditional dietary assessments, anecdotal evidence points to pink shrimp, blue crabs, fishes (clupeids, carangids, mullet, pinfish, mojarras, and kingfish), and stingrays as prey items. As opposed to stationary organisms such as oysters and benthic macrofauna, identification of essential habitat based on bathymetric and salinity attributes can be tenuous for mobile fish populations (Norton et al. 2012). This study recognizes the inherent complexity in linking freshwater discharge, salinity distributions, and sawfish habitat requirements. Thus, the objective of this effort was to quantify the extent of the nearshore habitat potentially available to sawfish under reduced inflow to the CRE.

Based on knowledge of the CRE morphology and inflow-salinity relationships, this study hypothesized that there would be a dry season inflow that would maximize the area where salinity ranged from 12 to 27 in shallow environments £ 1.0 m (**Figure A-66A**). While inflows less than the critical value allow salinity to encroach upstream where there is less shallow habitat, higher inflows may narrow the available habitat within the CRE (**Figure A-66B**). This study combined sawfish salinity requirements, bathymetric data for the CRE, and low inflow salinity distributions predicted using a three-dimensional hydrodynamic model, CH3D (**Figure A-67**).

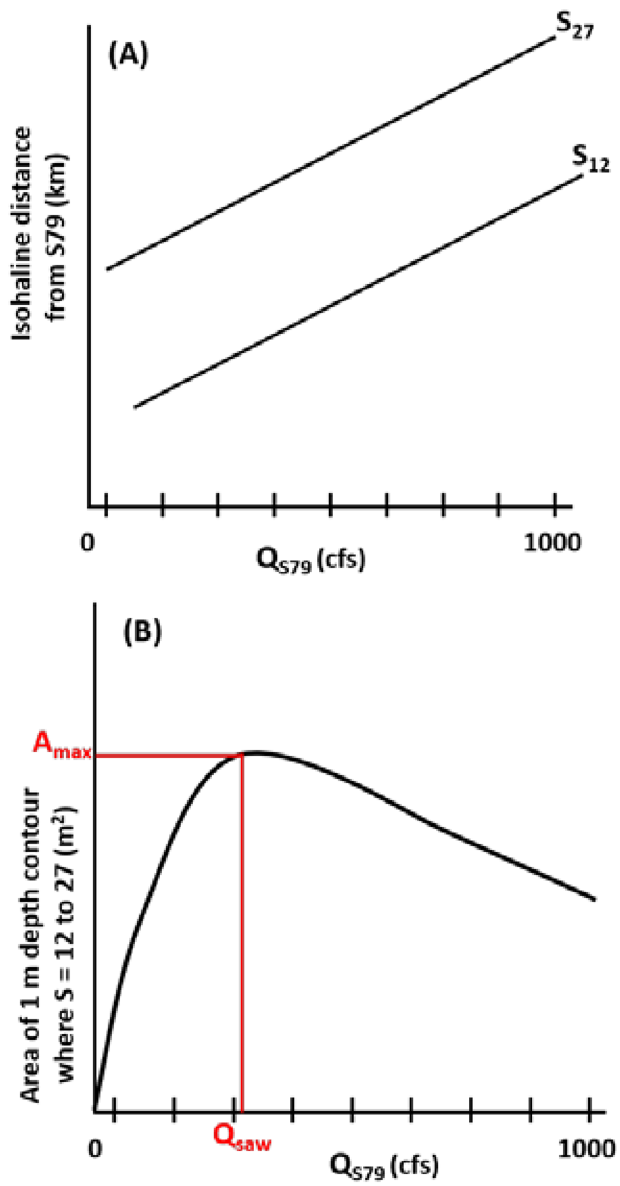


Figure A-66. (A) Hypothetical relationship between inflow at S-79 (Q_{S79}; cfs) and the downstream locations of the position of salinity S_{12} to S_{27}. (B) Hypothetical relationship between inflow at S-79 and the area for sawfish in the CRE.
(Note: A_{max} – maximum area; Q_{saw} – inflow that maximizes habitat area; and S – salinity.)

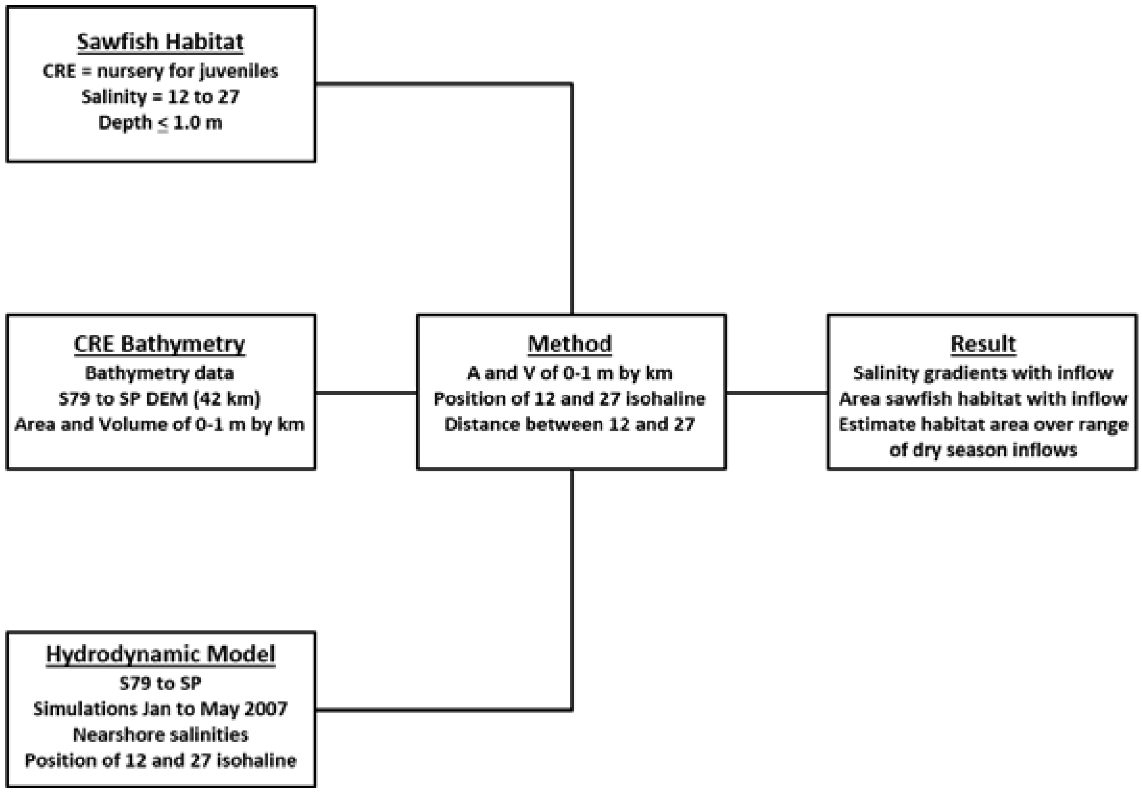


Figure A-67. Schematic of method used to combine sawfish habitat requirements, the bathymetry of the CRE, and the hydrodynamic model (CH3D) to estimate A_{saw}. (Note: A – A_{saw}, sawfish habitat area; V – V_{saw}, sawfish habitat volume; DEM – digital elevation model; Jan – January; and SP – Shell Point.)

Methods

Bathymetric Analyses

Three separate bathymetric data sets were merged to create a digital elevation model of the CRE (**Figure A-67**). Data collected in the estuary between Beautiful Island and Shell Point by USACE (2000) and USGS (2002) were combined with data collected between S-79 and Beautiful Island by SFWMD (2014). Aerial photography was digitized to provide a shoreline boundary for the digital elevation model. The digital elevation model was divided into 42 1-km segments between S-79 and Shell Point. The area and volume of the 0- to 1-m depth contour was quantified for each of the 42 segments.

Hydrodynamic Modeling

The CH3D model, originally developed by Sheng (1986), is a non-orthogonal curvilinear grid model capable of simulating complicated hydrodynamic processes including wind- and density-driven processes and tidal circulation. The model has a robust turbulence closure scheme for accurate simulation of stratified flows in estuaries and coastal waters (Sheng 1986, 1987). The non-orthogonal nature of the model enables it to represent the complex geometry of a tidal estuary such as the CRE. The model includes a circulation model to simulate three-dimensional hydrodynamics and a salinity model to simulate salt transport. The model is driven by external forcing prescribed at the boundaries including tidal forcing at the ocean boundary, freshwater inflow from the watershed, and meteorological forcing including wind and rainfall. The CH3D model has been successfully developed for many waterbodies including east coast Florida estuaries such as the Indian River Lagoon, St. Lucie Estuary (Sun 2009), and Loxahatchee River Estuary (Sun 2004).

The CRE CH3D model was developed from the Charlotte Harbor CH3D model (Sheng 2002). The original Charlotte Harbor model was calibrated using two months of hydrodynamic and salinity data collected during summer 1986 at six stations located in and around Pine Island Sound and the Peace River. SFWMD extended the model to the CRE using 16 months of continuous salinity monitoring data (Qiu 2002, SFWMD 2003). The CRE CH3D model was further calibrated with three years of salinity observations (October 2001–December 2004) at five stations in the estuary for the evaluation of various alternative plans of the Southwest Florida Feasibility Study and the C-43 Reservoir (Sheng and Zhang 2006, Qiu et al. 2007, USACE and SFWMD 2010). An external peer review of the CH3D model was conducted in 2006 for this application (Qiu 2006). The latest calibration of the model was conducted with data collected up to 2010 at seven locations in the estuary to support the development of the Lake Okeechobee Adaptive Protocols (SFWMD 2010, Wan et al. 2013).

The CRE CH3D model domain covers the entire estuarine system, including CRE, Charlotte Harbor, Pine Island Sound, San Carlos Bay, Estero Bay, and the major tributaries, as well as about 30 km offshore in the Gulf of Mexico. In the horizontal dimension, the grid has 166 x 128 elements allowing fine enough resolution to represent the numerous islands, including the islands of the Sanibel Causeway. The higher resolution within the CRE and San Carlos Bay (50 to 100 m) provides a more detailed representation of the complex shoreline and the navigation channel. Five vertical layers evenly spaced over the water column enable simulation of density stratification within the estuary.

The hydrodynamic model was applied in a test mode to generate salinity distributions over a range of S-79 inflows indicative of the dry season. Sawfish habitat was defined as the area (A_{saw}) (or habitat volume [V_{saw}]) of the estuary where depth was £ 1 m and surface water salinity ranged from 12 to 27 (**Figure A-67**). WY2007 was selected as the test case because it is within the POR for which the model has been calibrated and freshwater inflow was near the long-term minima. Simulations were from January 1, 2007, to May 31, 2007. The existing boundary conditions included empirical inputs for water level at the ocean boundary, rainfall, and wind at the surface, and estimated Tidal Basin runoff. These boundary conditions were applied over the entire simulation period. While observed S-79 freshwater inflows were applied from January 1, 2007, to February 28, 2007, a constant inflow was applied for the remaining time for each model simulation. This method was used because the model dynamics had to be established before the inflows could be manipulated. A total of seven simulations were performed for constant flow at S-79 of 0, 150, 300, 450, 650, 800, and 1,000 cfs. Based on long-term inflow records from WY1966 to WY2014, May has the lowest average rate of discharge through S-79 (761 ± 569 cfs). Thus, salinities from May 2007 from each of the simulations were used in sawfish habitat calculations.

Data Analyses

Surface salinities predicted for the nearshore areas using the hydrodynamic model along the northern and southern shorelines were averaged between S-79 and Shell Point. The average nearshore surface salinity then was plotted versus distance downstream of S-79 to visualize the salinity gradient for each of the seven constant inflows. Similarly, the area and volume of 0- to 1-m depth contour from the bathymetric analysis were plotted versus distance. The downstream positions of the 12 and 27 isohalines (S_{12} and S_{27}) were plotted versus the series of constant inflows. A_{saw} was derived by summing the area of bottom £ 1 m between S_{12} and S_{27} (millions of $m^2 = 10^6$ $m^2 = 1$ km^2). V_{saw} (millions of $m^3 = 10^6$ m^3) was calculated similarly as the volume of the 0- to 1-m depth contour for each km of estuary located between S_{12} and S_{27} was summed. A_{saw} and V_{saw} were plotted versus each of the constant inflows. A polynomial curve was fit to the scatterplot between A_{saw} and inflow at S-79 (Q_{S79}; cfs) as a tool to predict the A_{saw} as a function of dry season inflows.

Results

Depth ranges from 0.5 to 6.5 m in the CRE (**Figure A-68A**). Approximately 58% of the CRE is < 1.0-m depth (**Figure A-68B**; Buzzelli et al. 2013a). The area of the 0- to 1-m depth contour within each 1-km segment ranged from 0.01 x 10^6 to 0.53 x 10^6 m^2 (**Figure A-69**). These shallow depths were more prevalent from ~10 to 20 km downstream of S-79. Although the values increased with decreasing discharge, salinity was stable and nearly constant from S-79 and ~10 km downstream (**Figure A-70**; Buzzelli et al. 2014a). When there was no inflow, salinity was > 20 from 0 to 10 km before increasing to 35 near Shell Point. Similarly, salinity was > 14 in the upper CRE with 150 cfs of inflow. Because salinity was > 12 at S-79 for both of these inflow classes, the potential area of sawfish habitat was estimated to extend from the water control structure to the downstream location of S_{27}. Conversely, salinities were < 27 throughout the CRE for the 1,000-cfs inflow class. Thus, A_{saw} could not be estimated for the highest inflow tested since S_{27} was located outside of the estuary domain.

The distance between the S_{12} and S_{27} ranged from ~19 km when inflow was 0 cfs to 26.7 km when inflow was 150 cfs (**Figure A-71A**). This finding led to maximum values for A_{saw} (5.7 km^2) and V_{saw} (2.8 x 10^6 m^3; **Figure A-71B**). A polynomial curve was fit to the relationship between A_{saw} and inflow at S-79 to estimate sawfish habitat area over a full range of inflows indicative of the dry season (**Figure A-71C**). A_{saw} was maximized when inflow was 270 cfs.

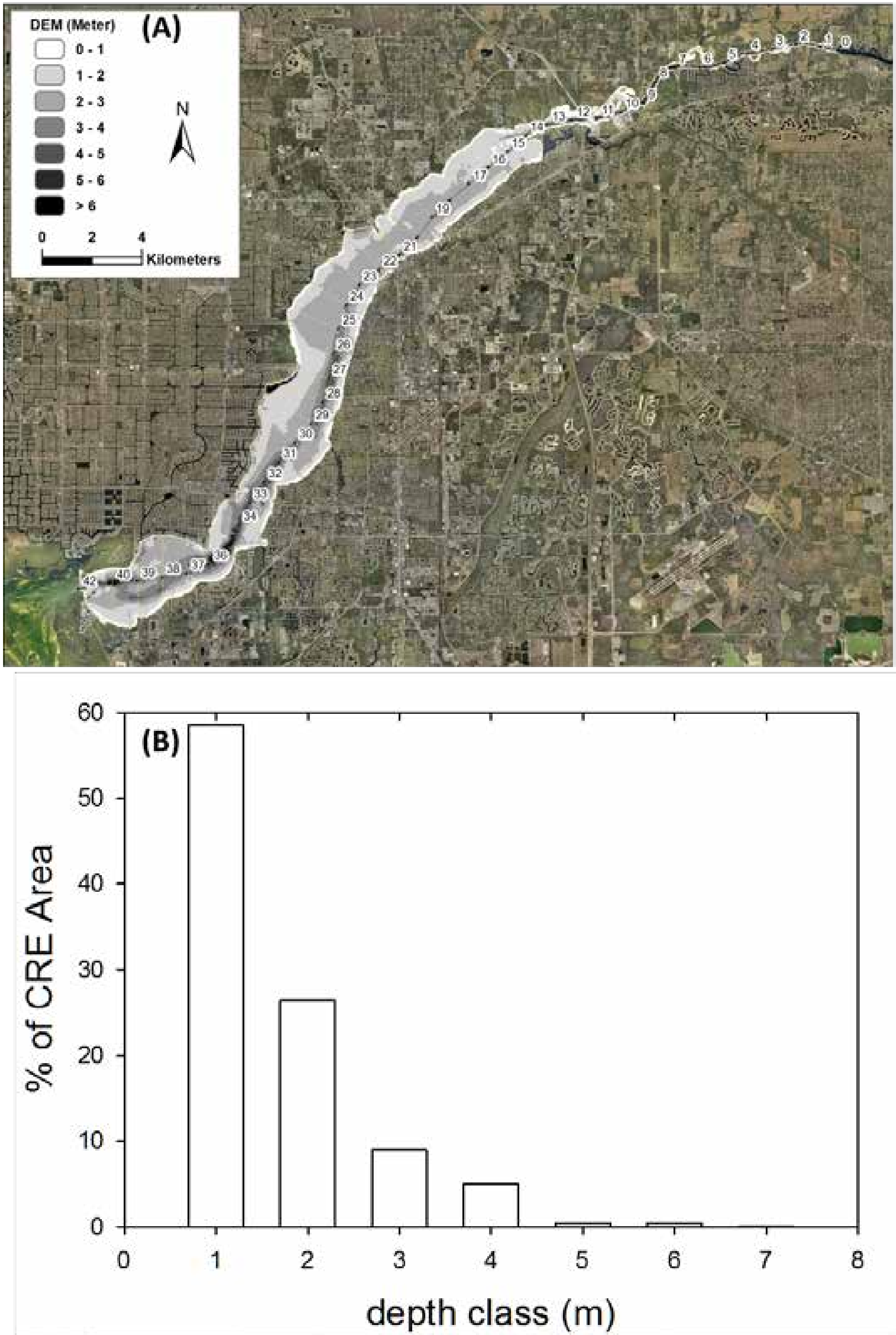


Figure A-68. (A) Bathymetric contour map for the CRE. (B) Frequency histogram depicting the bottom area for each of several CRE depth classes.

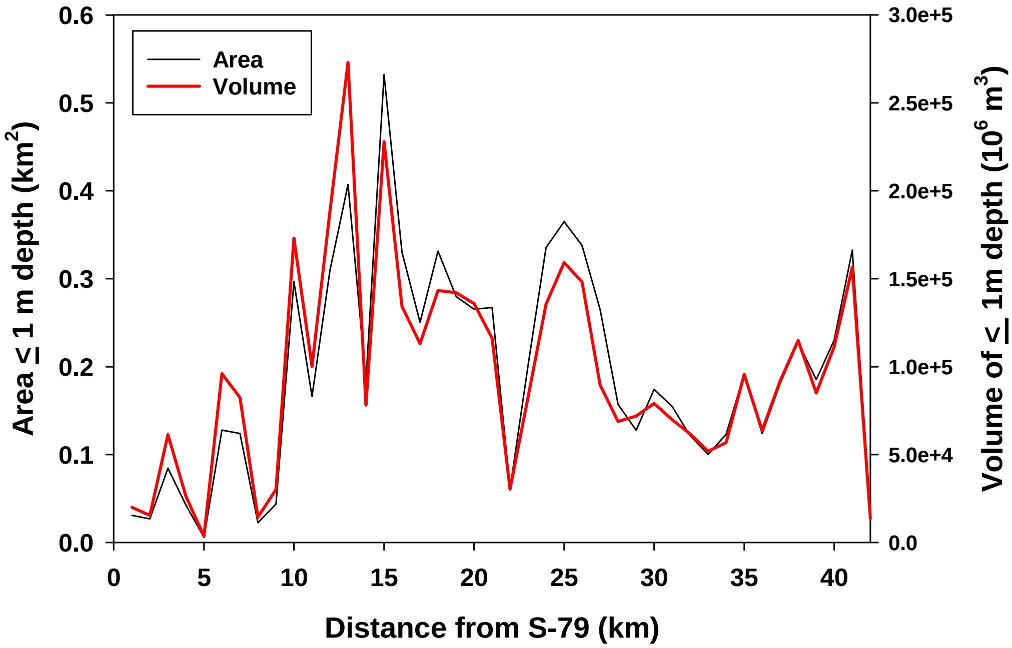


Figure A-69. Results of bathymetric analyses depicting the area and volume of the 0- to 1-m depth contour relative to distance downstream of S-79.

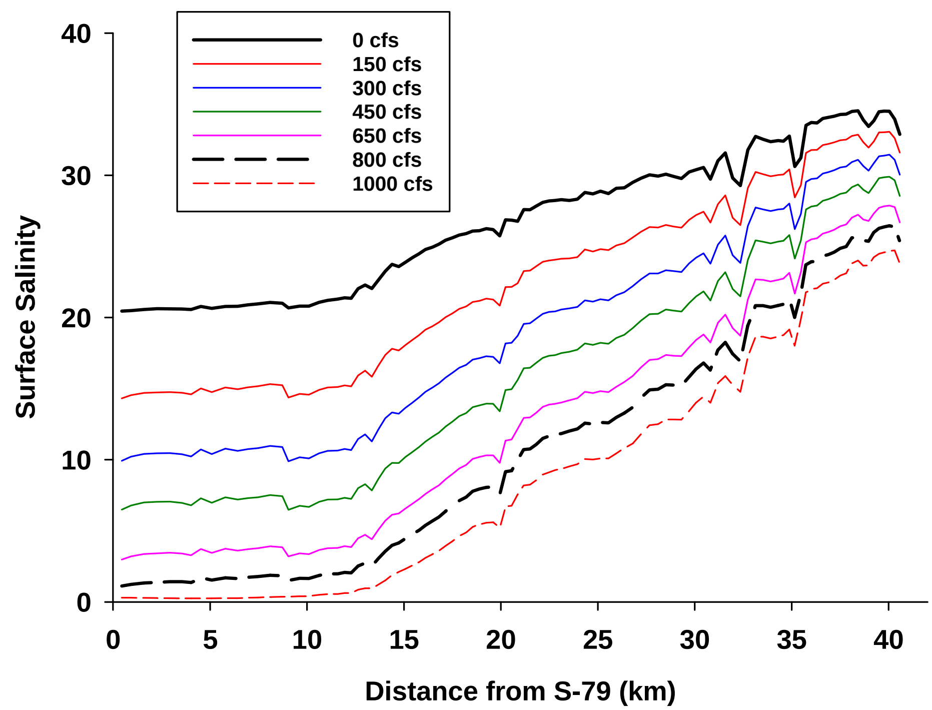


Figure A-70. The gradient in average salinities in nearshore environments predicted over a range of inflows (0, 150, 300, 450, 650, 800, and 1,000 cfs) from May 2007.

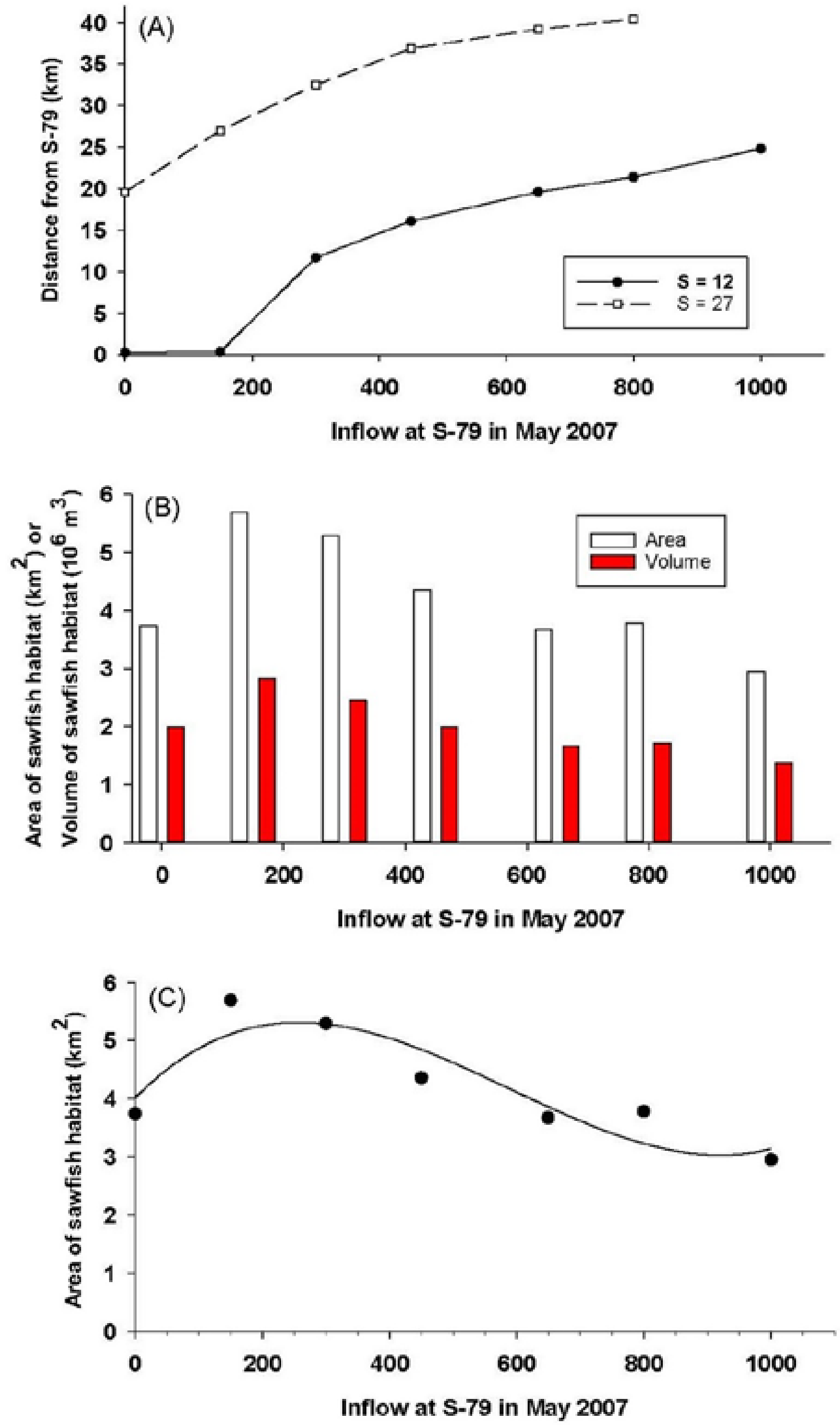


Figure A-71. (A) The position of the S_{12} and S_{27} salinity isohalines as a function of dry season inflow. (B) The A_{saw} and V_{saw} as a function of dry season inflow. (**C**) Scatterplot and polynomial curve fit between inflow at S-79 and the A_{saw}.

Discussion

An estimated 95% of the historical smalltooth sawfish population from Texas to North Carolina has been lost (Heupel et al. 2007, Norton et al. 2012). Salinity tolerance, food availability, and protection from predators are among the variables that characterize sawfish habitat. Although they can have widespread distribution depending upon age, *Pristis pectinata* can be found across a wide range of salinity values though they generally prefer 12 to 27 (Poulakis et al. 2013). This study connected knowledge of sawfish habitat requirements with spatial analyses of the bathymetry and a three-dimensional hydrodynamic model to estimate changes in sawfish habitat area in the CRE with inflow in the dry season.

Combined bathymetric and modeling results suggested that the maximum A_{saw} occurred when the inflow was 270 cfs in May 2007. May 2007 was selected because there was no freshwater input through S-79 and occurred in one of the driest years on record. This inflow (270 cfs) would position the 12 to 27 salinity range ~10 to 30 km downstream of S-79 (above Beautiful Island to Cape Coral). Sawfish habitat area between S-79 and Shell Point would be greatest under these conditions (~5.5 km^2). Less than 270 cfs could confine the sawfish habitat to the deeper upper CRE where there is much less shoal area, and lead to habitat compression against the structure. Upstream migration into a bathymetrically compressed habitat potentially places juvenile sawfish in closer proximity to larger predators such as bull sharks (Poulakis et al. 2011). At the other end, dry season inflows > 800 cfs should push the S_{27} out of the CRE and extend the sawfish habitat into San Carlos Bay.

Addendum to Component Study 11

Recalculation of Habitat Area with Respect to a Different Optimum Salinity Range for Sawfish

Poulakis (personal communication, 2016) suggests a different optimum salinity range from 18 to 30 to be used for juvenile sawfish in the CRE. Habitat area was recalculated based on the same hydrodynamic modeling results (**Figure A-70**) and bathymetric data. As discharge increases, habitat area and volume (**Figures A-72B** and **A-72C**) decreases. This is because as discharge increases, both isohalines of the 18 and 30 are pushed downstream, but the retreat of the 30 isohaline cannot make up the loss of area due to the retreat of 18 isohaline (**Figure A-72A**). It appears, that for this range of salinity, there would not be an optimum flow that maximizes the habitat area or volume for the sawfish.

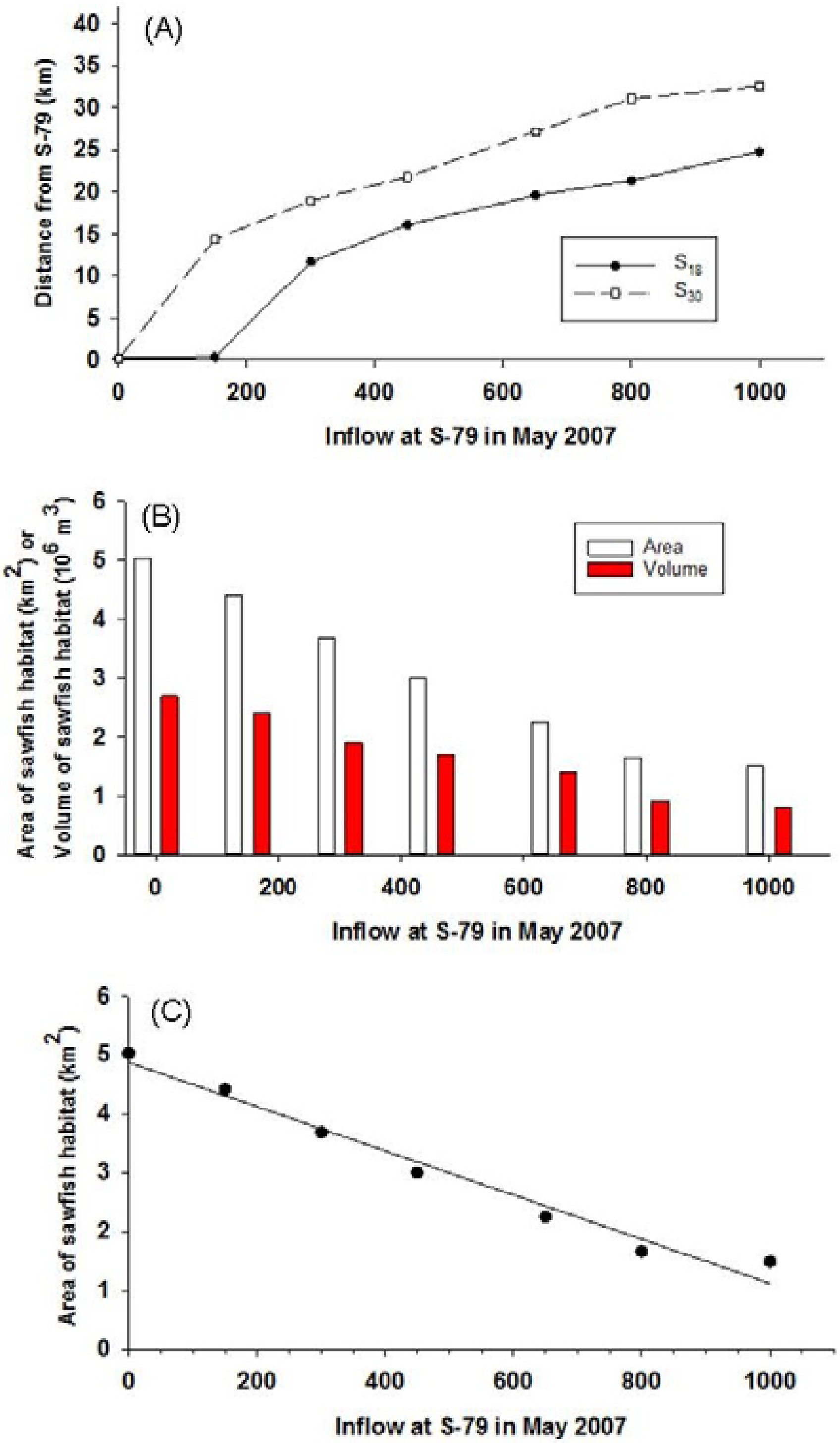


Figure A-72. (A) The position of the S_{18} and S_{30} isohalines as a function of dry season inflow. (B) The A_{saw} and V_{saw} as a function of dry season inflow. (**C**) Scatterplot and polynomial curve fit between inflow at S-79 and the A_{saw}.

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ATTACHMENT A-1: PUBLIC COMMENTS AND RESPONSES TO *ASSESSMENT OF THE RESPONSES OF THE CALOOSAHATCHEE RIVER ESTUARY TO LOW FRESHWATER INFLOW IN THE DRY SEASON*, AUGUST 2016 DRAFT

This attachment provides the reader with a summary of public comments received during and after the two-day public Caloosahatchee Science Symposium held in Fort Myers on September 14–15, 2016 (agenda provided). The symposium was held to present a scientific assessment conducted by SFWMD that was summarized in the August 2016 draft science document titled *Assessment of the Responses of the Caloosahatchee River Estuary to Low Freshwater Inflow in the Dry Season.* This version of the draft science document was made available to the public for review and comment 30 days prior to the symposium, and an additional 30-day comment period followed the symposium. All verbal and written comments received before, during, and after the symposium were reviewed by SFWMD, and where appropriate, they were addressed in the final science document.

Many of the public comments contained in this appendix refer to page and line numbers only included in the August 2016 draft science document. For reference, the August 2016 version of the science document can be obtained online at https://www.sfwmd.gov/our-work/mfl or by request to Don Medellin at dmedelli@sfwmd.gov.

Agenda of Caloosahatchee Science Symposium

September 14–15, 2016

South Florida Water Management District/Lower West Coast Service Center
2301 McGregor Boulevard, Fort Myers, FL 33901

Study	**Description**	**Presenter**	**Time**
Day 1 (Wednesday, September 14, 2016)			
Morning Session – Physical Studies:			
	Introduction and Objectives	Don Medellin	10:00 – 10:30
	Overview of the Caloosahatchee Estuary	Peter Doering, Ph.D.	10:30 – 11:00
Hydrodynamics	Influence of alterations on hydrodynamics	Detong Sun, Ph.D.	11:00 – 11:30
Inflows vs. Salinity	Monthly freshwater-salinity relationships at Ft. Myers	Chris Buzzelli, Ph.D.	11:30 – 12:00
	Lunch – On Your Own	**All**	12:00 – 1:30
Afternoon Session – Water Column Studies:			
Water Quality	Fine scale relationships between water quality and inflow	Chris Buzzelli, Ph.D.	1:30 – 2:00
Zooplankton	Inflow, zooplankton and habitat compression	Peter Doering, Ph.D.	2:00 – 2:30
	Break	**All**	2:30 – 2:45
Ichthyoplankton	Relationships between ichthyoplankton and inflow	Cassondra Thomas, Ph.D.	2:45 – 3:15
	Question/Answer Session	**All**	3:15 – 5:00
Day 2 (Thursday, September 15, 2016)			
Morning Session – Fauna Studies:			
	Introduction and Objectives	Don Medellin	9:00 – 9:15
Benthic Fauna	Macrofauna-salinity patterns relative to inflow	Chris Buzzelli, Ph.D.	9:15 – 9:45
Oyster Habitat	Assess conditions for oyster survival and growth in lower CRE	Chris Buzzelli, Ph.D.	9:45 – 10:15
	Break	**All**	10:15 – 10:30
Sawfish	Area and volume of sawfish habitat with variable dry season inflow	Detong Sun, Ph.D.	10:30 – 11:00
Blue Crabs	Relationships between blue crab landings, rainfall, and inflow	Peter Doering, Ph.D.	11:00 – 11:30
	Lunch – On Your Own	**All**	11:30 – 1:00
Afternoon Session – Flora Studies:			
Vallisneria data	Empirical relationships between tape grass, salinity, and inflow	Peter Doering, Ph.D.	1:00 – 1:30
Vallisneria model	Model exploration of tape grass, salinity, light, and inflow	Chris Buzzelli, Ph.D.	1:30 – 2:00
	Break	**All**	2:00 – 2:15
	Question/Answer Session	**All**	2:15 – 3:45
	Next Steps & Wrap-up	Don Medellin	3:45 – 4:00

THIS SYMPOSIUM IS OPEN TO THE PUBLIC. THE DRAFT SCIENCE SUMMARY IS AVAILABLE AT http://www.sfwmd.gov/mfl. COMMENTS ON THE DRAFT SCIENCE SUMMARY ARE REQUESTED TO BE SUBMITTED BY OCTOBER 14, 2016 TO: Don Medellin, Principal Scientist, South Florida Water Management District, P.O. Box 24680, West Palm Beach, FL 33406; (800) 432-2045, ext. 6340; (561) 682-6340; dmedelli@sfwmd.gov.

Comments from Caloosahatchee Science Symposium September 14–15, 2016

Date	Entity	Comment	Response
9/14/16	Florida Gulf Coast University	Component 1. Why didn't the modeling for Component 1 include the changes that occurred in the watershed with the physical alterations in the estuary?	The modeling exercise that was done was designed to look at systematic physical or structural changes or alterations (5 total) to the Caloosahatchee Estuary using a model that simulates estuarine circulation and salinity based on bathymetry, freshwater inflow, wind and ocean tides. The purpose was to isolate the effects of each alteration on salinity in the estuary. Modeling alterations or predevelopment conditions within the watershed were (a) not possible with the model we used and (b) beyond the scope of this analysis.
9/14/16	Sanibel Captiva Conservation Foundation (SCCF) – Rae Ann Wessel	Component 2. There is a concern that the flow estimates from S-79 (used in Component 2) to produce a salinity of 10 at Ft. Myers was too low and that documented higher flows were required.	Additional technical analysis was performed. A daily statistical analysis was performed using the average daily values. Results were compared to data received from SCCF staff and to the results presented in Component Study 2. See additional technical analysis in **Attachment A-2**.
9/14/16	Eric Milbrandt	Component 2. There seems to be an increasing trend over the 20 year period. Should consider a trend analysis of all years for Qcalcs.	The magnitude of the inflow associated with S10 at Ft. Myers is inversely correlated to rainfall the previous dry season. No trend.
9/14/16	City of Sanibel – James Evans	Component 4. Suggested that staff evaluate the effects of gelatinous predators and the potential for prey when habitat compression or impingement occur.	See Addendum to Component Study 4.
9/14/16	City of Sanibel – James Evans	What months are within the wet and dry seasons that was evaluated?	The wet season is November–April and the dry season is May–October.
9/14/16	SCCF – Rae Ann Wessel	There are two different studies that indicate the flows at S-79 should be much higher than 300 cfs – Tolley study indicated the flows should be 1200 cfs. How do you reconcile these flow differences?	The Tolley et. al (2010) study made several estimates of critical inflows for zooplankton ranging from 800 to 1,200 cfs. These estimates were based on relationships between flow and center of abundance, total abundance, and position of the 90th percentile of population distribution. The estimates of critical flow are based largely on visual inspection of graphical plots. While there is nothing wrong with this approach, when the data are variable, what one investigator sees may not agree with what another sees. Since our analysis has to pass peer review, we used a statistical approach to avoid the potential of conflicting visual interpretations. The discrepancies between our analysis and the Tolley report arise from two sources. First, we used predetermined periods over which to average the flow data, rather than picking the lag with the highest correlation coefficient. Averaging periods were limited to those over which flows might be managed. This will affect flow

Date	Entity	Comment	Response
			estimates. Secondly, there are some statistical considerations. The impingement analysis will serve as an example. Taking into account the associated error, any one of the statistical estimates for individual taxa overlaps the 1,000-cfs estimated by Tolley. However, the central tendency of results for the 7 taxa is about 400 cfs. Our approach along with results and attendant errors were presented in the report and at the workshop.
9/15/16	Florida Fish and Wildlife Conservation Commission – Gregg Poulakis	Component 11. Based on data from the Caloosahatchee, the preferred salinity range of the smalltooth sawfish is 18-30 psu. Mr. Poulakis Suggested revising the analysis.	See *Addendum to Component Study 11*.
9/15/16	SCCF – Rae Ann Wessel	General Comment. The monitoring data is flawed because we are paying to restore/replant tape grass in the estuary which may skew the monitoring data (Vallisneria Data-Component 7).	Since monitoring began in 1998, investigators were careful to locate restorative plantings away from monitoring sites so there is no direct effect on monitoring results. Restorative planting may influence monitoring sites by supplying seeds. This may enhance the rate of recovery when salinity and light conditions are favorable. Identifying stressful conditions is relevant to the MFL. There is no evidence that restorative plantings have served as a seed source to monitoring sites in the estuary. No restorative planting has established a permanent tape grass bed. Like native populations, transplants have died when conditions become stressful.

Written Public Comments (Letters) Received by SFWMD

Date	Entity	Comment	Response
10/21/2016	Sanibel Captiva Conservation Foundation (SCCF) – Letter	General Comment-Page 1 of SCCF Letter. There has been a permanent loss of approximately 1,000 acres of tape grass.	There is no supporting documentation of a permanent loss of 1,000 acres of tape grass. The only relatively accurate assessment of tape grass in the CRE was done by Hoffacker in 1993, a year that in Hoffacker's opinion exhibited unusually lush and widespread growth of SAV, including tape grass. There may be 1,000 fewer acres of tape grass today then there were in 1993, but 1993 was atypical. Claiming a 1,000-acre loss based on an atypically dense and widespread distribution is technically flawed.
10/21/2016	SCCF – Letter	General Comment-Page 1 of SCCF Letter. The MFL target is based on the original field research was done under a different regulation schedule held several feet higher than the current LORS 08 schedule and during a wet climate cycle (1990s). The current schedule holds water levels lower within Lake Okeechobee and coincides with several consecutive years of drought.	The response of organisms to changes in salinity and flow that forms the basis of the current MFL criteria will be the same no matter how climate has fluctuated or regulation schedules have changed over the past 20 years. What does change on an annual basis is the amount of water required at S-79 to achieve a salinity of 10 at the Ft. Myers station. See Component Study 2.
10/21/2016	SCCF – Letter	Component 1-Page 1 of SCCF Letter. SCCF agrees that alterations during from the 1880s-1960s have caused impacted resources before these alterations occurred. SCCF is concerned that these alterations are a prominent reference point in the District analysis.	See Section 373.0421, F.S..
10/21/2016	SCCF – Letter	Component 2-Page 2 of SCCF Letter. Dr. Bartleson's analysis of an exponential curve fit for salinity data from the Ft. Myers Yacht Basin and the 30-day avg. flow from S-79 showed a regression equation that calculates 10 psu at 620 cfs.	SFWMD requested the raw data that SCCF used to generate this exponential curve. It was not provided. From the information we did get from SCCF, we could not reproduce the curve, despite our best efforts. The District analyzed the relationship between flow at S-79 and salinity at Ft. Myers and compared its results to Dr. Bartleson's. See Component Study 2 and additional technical analysis in **Attachment A-2**.
10/21/2016	SCCF – Letter	General Comment-p.iii Line 41 in Draft Science Document (August Draft). The Caloosahatchee estuary should include San Carlos Bay to determine the MFL. Truncating the boundary of the estuary does not allow for a complete analysis of the effects of dry season inflow to determine the MFL	The science reevaluates the MFL based on the boundary of the adopted MFL and all available science data was taken into consideration. San Carlos Bay is the downstream limit of the adopted MFL Rule 40E-8.021(2), F.A.C.. From a technical perspective, it is evident that the response of salinity to low flows at Shell Point and beyond is relatively sluggish. The same change in flow at S-79, causes a proportionally smaller change in salinity as distance from S-79 increases. According to Qiu and Wan 2013, an increase in flow from 0 cfs to 1,000 cfs would change salinity at

Date	Entity	Comment	Response
			the I-75 Bridge from 31.86 to 0 or by 100%. The same change in flow 0–1,000 cfs at Cape Coral would reduce salinity from 21.42 to 15.86 (25%). At Shell Point, salinity would change from 30.58 to 26.32 (14%). It is the upper estuary that is most responsive and sensitive to low flows. Setting the boundary of the estuary at Shell Point rather than San Carlos Bay does not materially affect our analysis.
10/21/2016	SCCF – Letter	Executive Summary-p.iii Line 41 in Draft Science Document (August Draft). To account for the variability around the mean a conservative approach could take the average flow for each indicator and add the positive range of variability to prevent significant harm (545+ 774 = 1319 cfs for tape grass). This method will take into account the inter-annual variability in rainfall and acceptable range of flows for setting the MFL.	It is not statistically valid to only consider the positive portion of the standard deviation around a mean. The entire range of flows should be considered. Additionally, the mean and range of flows for multiple ecological indicators must be carefully considered when determining an appropriate MFL, otherwise, the flow for one ecological indicator could be detrimental to other indicators.
10/21/2016	SCCF – Letter	Science Summary-p.11 Line 1059. Q1 estimates should also consider the range of flows caused by high interannual variability	Interannual variability is explicitly or implicitly included in estimates of Q1. For Component Study 2, a separate analysis is done for each year and results are then averaged. Interannual variation is therefore explicitly included. For other analyses, such as Component Study 9, the days upon which a given salinity criterion was exceeded were identified over a POR spanning many years (in this case WY2005–WY2014). Flows at S-79 on those days were averaged. Again, since a multiyear POR was analyzed, interannual variability is included. Since averaging was on a daily time scale, rather than an annual one, the differences between years are represented implicitly.
10/21/2016	SCCF – Letter	Component 4 (p.11 Line 1137). Based on a study done by S.G.Tolley, it appears that freshwater flows on the order of 800-1000 cfs would be sufficient to release these organisms from impingement caused by the S-79 lock and dam. How can the re-analysis results presented and conclusions be so different, especially since it's the same data?	The Tolley et al (2010) estimated that flows in the range of 800–1,000 cfs would alleviate impingement on S-79. These estimates were based on relationships between flow and the position of the 90th percentile of population distribution. The estimates themselves are largely based on visual inspection of graphical plots. While there is nothing wrong with this approach, when the data are variable, what one investigator sees may not agree with what another sees. Since our analysis has to pass peer review, we used a statistical approach to avoid the potential of conflicting visual interpretations. The discrepancies between our analysis and the Tolley report arise from two sources. First, we used predetermined periods over which to average the flow data, rather

Date	Entity	Comment	Response
			than picking the lag with the highest correlation coefficient. Averaging periods were limited to those over which flows might be managed. This difference will affect flow estimates. Secondly, there are some statistical considerations. Taking into account the associated error, any one of the statistical estimates for individual taxa overlaps the 800–1,000-cfs estimated by Tolley. However, the central tendency of results for the 7 taxa is about 400 cfs. Our approach along with results and attendant errors were presented in the report and at the workshop.
10/21/2016	SCCF – Letter	Components 7 and 8 (p.13; Lines 1204-1208) are inconsistent in the salinity targets for Ft. Myers. Component 7 set Q1 targets to achieve salinities of 9-10 at FTM while Component 8 used annual-inflow-salinity relationships to hold salinities at 12 which led to shoot mortality in the model. Flow estimates are too low to support the previous studies or model runs.	The empirical analysis of salinity and *Vallisneria* (Component Study 7) targeted a salinity of 9–10 as the upper limit for limited growth. The simulations (Component Study 8) were conducted to determine the salinity where *Vallisneria* suffered net mortality. Thus, a salinity of 12 resulted from the model study.
10/21/2016	SCCF – Letter	Component 9: p13 Line 1219. Why were salinities at Cape Coral targeted for salinities ranging from 20-25? Flows necessary to keep salinities above 25 at Shell Point should have been used for calculating minimum flows, not Cape Coral. This approach used upstream sites for calculating flow/salinity relationships appears to favor a lower minimum flows. Why not use real-time data and adaptive management to hit the salinity targets?	As detailed in Component Study 9, the premise is that the upper boundary for oyster habitat (e.g., Cape Coral) was the location to assess for potential effects of elevated salinity. Oyster habitat is not a good indicator for the CRE. A majority of the habitat is downstream near Shell Point where salinity is > 20–25 ~85% of the time. Powell (2017) examines Gulf of Mexico oysters and probable mechanisms of Dermo. Salinity is not a controlling variable. Reference: Powell, E.N. 2017. What Is going on with *Perkinsus marinus* in the Gulf of Mexico? *Estuaries and Coasts* 40:105-120.
10/21/2016	SCCF – Letter	Component 10 (p.13; Line 1224). Higher flow (>1000 cfs) may be important in the short-term recovery of the blue crab fishery.	For our analysis, we assumed that recovery occurred under conditions of average rainfall. The focus of our analysis was not to identify flows that promote recovery, rather to identify those that cause significant harm.
10/21/2016	SCCF – Letter	Component 11 (p.14; Line 1240). Why weren't 30 day average flows used for the 30 day average salinities at the Yacht Basin used in the re-analysis?	The hydrodynamic model application was a test case for WY2007. Discharge at S-79 was held constant in the last 3 months of simulation. In this sense, the flow can be considered a 30 day average and salinity is the equilibrium for the flow.
10/21/2016	SCCF – Letter	Science Summary-p.14; Line 1253. The 10 component studies used different flow and salinity for Q1. The same selection criteria were not used and each had different study periods, different locations and larger inter and intra annual variability and, therefore,	(1) The data used to generate the 237 + 255 cfs were based on a study conducted by Robert Chamberlain (1986–1989). Not at all the same data as used by Tolley et. al (2010). (2) How the various estimates of flow magnitude from the 10 studies are combined into a final

Date	Entity	Comment	Response
		cannot be lumped together and a median selected out of thin air. The report is a nice review but the "same selection criteria" were not used and differ greatly from the conclusions of the original report 800-1000 cfs (Tolley) versus 237+255 for icthyoplankton even though the same data were used. It appears that the S-79 flow estimates are purposefully analyzed to show low flows, in some cases. How will the target to minimize harm be chosen from such different approaches?	estimate is important and critical. The approach that we use to choose the flow target will be detailed in the technical document that supports rulemaking. (3) The MFL will be peer reviewed by a panel of impartial experts.
10/21/2016	SCCF – Letter	Science Summary-p.15; Table 2 and p.17; Line 1292. The months for the dry season should be expanded to include May and October to reduce inter-annual variability in flow and salinity. The most significant problem with this table is that not all of the components used the same 30-day average 10 psu criteria at FTM which is the basis for the rule. The flow numbers can't be compared in a table because the criteria are for each differed. One median flow based on all of these components is not valid. If this approach is used then each component should be reanalyzed and include the 30-day average salinity not to exceed 10 at FTM.	We have used a standard definition for wet and dry seasons that is used for reporting under the Northern Everglades and Estuaries Protection Program in the South Florida Environmental Reports. The analyses presented in the document were intended to elucidate the response of a series of estuarine indicators to low freshwater inflows during the dry season. These analyses were not intended to test the efficacy of the 30-day average, salinity of 10 criterion that is part of the current rule.
10/21/2016	SCCF – Letter	Science Summary (Component 4)-p.16; Table 3. The original zooplankton study concluded 800-1000 cfs. The Val model is too low because they used salinities of 12 at FTM to determine S-79 flows. These ranges are not comparable because different selection criteria for flow were used.	It was not the intention of this analysis to evaluate the current MFL criteria (i.e., 30-day average salinity of 10 at Ft. Myers or daily average of 20). Rather it was to analyze as much data as possible from as many sources as possible and to let the results of these analyses form the basis of MFL criteria.
10/21/2016	SCCF – Letter	Science Summary (Component 9)-p.19; Line 1380. Oyster habitat at Cape Coral should not be used the salinity target location. The analysis should not use the upper freshwater limit of distribution but the center of abundance similar to the other studies (ichthyoplankton, zooplankton and Vallisneria)	As detailed in Component Study 9, the premise is that the upper boundary for oyster habitat (e.g., Cape Coral) was the location to assess for potential effects of elevated salinity. Oyster habitat is not a good indicator for the CRE. A majority of the habitat is downstream near Shell Point where salinity is > 20-25 ~85% of the time. Powell (2017) examines Gulf of Mexico oysters and probable mechanisms of Dermo. Salinity is not a controlling variable. Reference: Powell, E.N. 2017. What Is going on with *Perkinsus marinus* in the Gulf of Mexico? *Estuaries and Coasts* 40:105-120.

Date	Entity	Comment	Response
10/21/2016	SCCF – Letter	Science Summary-p.19 Line 1388. Acknowledgement of re-analysis results from widely different approaches but then conclusions from Table 2 using the "same selection criteria." Why does the estuary boundary end at Glover's bight and not Sanibel Lighthouse?	The boundary of the adopted MFL for the Caloosahatchee River is defined in Rule 40E-8.021 (2), F.A.C.. San Carlos Bay is the downstream boundary of the adopted MFL. See response to similar comment above.
10/16/16	Hidetoshi Urakawa, Associate Professor, Florida Gulf Coast University (FGCU) – Letter	Science Summary. Uncertainty itself is not important but how to address is important. Therefore, I think "Interpretation of Uncertainty", "Understanding of Uncertainty" or some similar heading is better. [refers to Importance of Uncertainty section near the front of the Science Summary]	These edits were made.
10/16/16	FGCU – Letter	Component 2-Methods. Please add a brief explanation of WY.	These edits were made.
10/16/16	FGCU – Letter	Component 2- Discussion. The statement is inscrutable. To explain the observed great variability, it says the amount of ungauged freshwater input from the Tidal Basin is a key component to the total freshwater budget. According to this statement, the Tidal Basin flow is likely not measured yet. But the last sentence says these inputs have been incorporated into a published model. It is hard to understand the interaction between presented data and the current discussion. P.S. The Tidal Basin flow is 21% according to line 3900 in Component 10.	The amount of water required to make a salinity of 10 is also dependent on previous year's rainfall, not just tidal basin inflow.
10/16/16	FGCU – Letter	Component 2-Results [Figure 14]. "Monitoring station" is missing from this part of the caption [it is included in the caption for the figure above this one]. Is it on purpose?	No edits were made.
10/16/16	FGCU – Letter	Component 3. I think it is good if the authors mention that hypoxia events of CRE are not a critical issue for the overall ecology of the estuary in this point and limited to an upstream deep channel.	No edits were made.
10/16/16	FGCU – Letter	Component 3. It is fine, but no historical events are discussed. Are there any past ecological disasters associated with hypoxia? If not, it should be stated here for better understanding of the level of hypoxia problem in the CRE.	There are no past ecological disasters associated with hypoxia.
10/16/16	FGCU – Letter	Component 3. Figure 20 was not printed out correctly as a PDF file. It should be corrected.	No edits were made.
10/16/16	FGCU – Letter	Component 3. I think the authors should add a statement that the most part of CRE	No edits were made.

Date	Entity	Comment	Response
		maintains a healthy condition in terms of DO level as a part of previous studies.	
10/16/16	FGCU – Letter	Component 3-Discussion (4th paragraph) “The model (269 cfs) and field results (469 cfs) indicated that freshwater…” is better than the current writing. The current writing is a bit confusing.	These edits were made.
10/16/16	FGCU – Letter	Component 5. Please delete “just downstream of Station 2”. Abstract should be independent and should not cite sampling stations at which the authors do not know.	These edits were made..
10/16/16	FGCU – Letter	Component 5. Do ichthyoplankton really include decapods? What is the meaning of “ichthyo-“? Ichthyoplankton should include fish eggs.	These edits were made..
10/16/16	FGCU – Letter	Component 5 Line 2667. Please delete “from a study conducted”.	These edits were made.
10/16/16	FGCU – Letter	Component 5 line 2705. COA. If this is the first time, please spell it out.	These edits were made.
10/16/16	FGCU – Letter	Component 5 line 2734. “Juvenile bay anchovy” is better than “juvenile fish”, if my understanding is correct.	Anchovy may not be the only species that seeks low salinity during the juvenile stage. No edits were made.
10/16/16	FGCU – Letter	Component 5 line 2736. Not “are” but “were”.	These edits were made.
10/16/16	FGCU – Letter	Component 5 line 2744. Could you rephrase the sentence? I am not sure [of] the meaning that juvenile fish abundance could serve as an indicator for freshwater inflow. Can we accurately estimate the flow rate based on ichthyoplankton data?	These edits were made.
10/16/16	FGCU – Letter	Component 5 line 2674-2677. Month zero should be corrected. I am not sure if crabs and shrimps were included in ichthyoplankton or zooplankton in this figure. Lines 2678-2681. Please make the statement clear if decapods are included in ichthyoplankton in this report.	These edits were made.
10/16/16	FGCU – Letter	Component 5 line 2757. This statement is redundant (see line 2735). [refers to the statement “Juvenile fish were most frequently found in salinities ranging from 4 to 6 with frequency of occurrence declining at salinities that were >10.”]	No edits were made.
10/16/16	FGCU – Letter	Component 5-Results and Discussion. Is this a standard deviation? It is quite large. A geometric mean might be better than an arithmetic mean. [refers to 255.5 cfs in the	This is an arithmetic mean and standard deviation as was done for all other flow ranges. It demonstrates the variability of the system. No edits were made.

Date	Entity	Comment	Response
		statement "The 30-day average inflows associated with these salinity values ranged from 12.3 to 1,357 cfs and averaged 237.5 ± 255.5 cfs" in Results and Discussion in Component Study 5].	
10/16/16	FGCU – Letter	Component 9. Please delete "mortality". Survival and mortality are similar meaning here.	No edits were made.
10/16/16	FGCU – Letter	Component 9. I like this figure but it is a bit unclear. The sizes of oysters in each box are different: small shell in a low salinity box while a large shell in a high salinity box. What do these differences stand for? Does y-axis mean survival or growth rate? What is a possible unit? [refers to Figure 56]	This figure is conceptual. The oysters are deliberately shown as different sizes to illustrate the effects of salinity on growth.
10/16/16	FGCU – Letter	Component 9-Table 29. It is understandable but Cape Coral (CC) and Shell Point (SP) is better.	These edits were made.
10/16/16	FGCU – Letter	Component 10-Abstract. CPUE and CRE should be spelled out when used first time.	No edits were made.
10/16/16	FGCU – Letter	Component 10-Methods. It is nice if the authors can define water year (WY) when it comes first time.	No edits were made.
10/16/16	FGCU – Letter	Component 10. It should be Table 33. [refers to a needed correction to the Table 33 reference shown in the text of Component Study 10]	These edits were made.
10/16/16	FGCU – Letter	Component 11. I believe these two paragraphs are not necessary in this component. It is simply redundant. Start from line 4230 is a good idea.	No edits were made.
10/16/16	FGCU – Letter	Component 11. Please add "their" in front of "pathogens".	No edits were made.
10/16/16	FGCU – Letter	Component 11. Is it correct? [refers to figure referenced in the Methods/Bathymetric Analyses section Component Study 11 as Fig. A11-2]	These edits were made.
10/16/16	FGCU – Letter	Component 11. The "-" looks like a "minus" sign. [refers to the Note with Figure 66]	These edits were made.
10/16/16	FGCU – Letter	Component 11. Same as last comment. The "-" looks like a "minus" sign. [refers to the caption with Figure 67]	These edits were made.
10/16/16	FGCU – Letter	Component 11. Labels of Figures A, B, and C are missing. [refers to Figures 71A, 71B, and 71B]	These edits were made.
10/16/16	Conservancy of Southwest	Component 1. Other factors outside of the physical alteration of the river, such as the loss of headwaters at Lake Hicpochee, over-	The modeling exercise were experiments to look at systematic physical or structural changes within the estuary with an emphasis on bathymetry. Modeling

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	Florida (CSWF) – Jennifer Hecker – Letter	drainage of the watershed (with resulting loss of base flow) which could increase salinity, and water management practices such as cutting off freshwater flows from Lake Okeechobee to the river also need to be assessed to determine the comparative influence they have on salinity.	alterations or predevelopment conditions within the watershed was beyond the scope of this analysis.
10/14/16	CSWF – Letter	Component 1. The Conservancy suggests running other [salinity] scenarios that take into account the Lake connection as well as a natural conditions scenario.	See our response provided above. The numerical experiments were designed to look at bathymetry changes and structural changes within the estuary and to isolate their effects. Applying S-79 flow explicitly includes the lake connection.
10/14/16	CSWF – Letter	Component 1. Using the existing flows with predevelopment hydrology, not predevelopment flows, seems questionable in our view and we would caution making any conclusions based on these results. It is not replicating predevelopment nor current day conditions, but is instead an artificial hybrid scenario that has never existed nor exist presently.	Again, the model analysis was designed to examine the impacts from physical and structural changes and was able to isolate the effects from different alterations and identify that bathymetry changes, especially deepening of the channel, had significant impact on salinity. This would be true regardless of whether predevelopment flow or current condition flow was used.
10/14/16	CSWF – Letter	Component 2. We are concerned that the analysis [of the amount of inflow needed at S-79 to achieve a desired salinity level] did not involve a trend analysis and [we] think that even at a monthly scale, it would be good to do a time lag of one to two weeks.	See the previous response. The amount of inflow associated with S_{10} at the Ft. Myers station is inversely correlated to rainfall the previous dry season. There is no trend.
10/14/16	CSWF – Letter	Component 2. The modeling used seems to significantly underestimate the flow needed at S-79 based on real world monitoring of the system. We recommend a reanalysis to incorporate the real world data on what flows have achieved the target salinity.	See the previous response. Component Study 2 was based on approximately 20 years of observed data.
10/14/16	CSWF – Letter	Component 2. The conclusion that flow needs are not anticipated to increase over time does not seem logical in our view given the continued reduction in base flow and the continued sea level rise that will undoubtedly occur, causing further saltwater intrusion into the system.	This is not a conclusion of this document.
10/14/16	CSWF – Letter	Component 4. We support the suggestion made by the City of Sanibel staff to include an analysis of increased predation in this effort to study zooplankton response to flows from S-79.	See the *Addendum to Component Study 4*.
10/14/16	CSWF – Letter	Component 11. The preferred salinity range used in the study presented for sawfish is 12-27 pus, extrapolated apparently from the Peace River. We support the more appropriate salinity range for the	See the *Addendum to Component Study 11*.

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		Caloosahatchee that FWC provided at the meeting, 18-30 psu, to be used for rerunning or future analysis.	
10/14/16	CSWF – Letter	Component 11. The SFWMD's resource-based approach involving seven indicators does not address the needs of all endangered species using the Caloosahatchee. The Conservancy recommends adding endangered species as an indicator to specifically look at both the direct and indirect effects of flows on all endangered species using the Caloosahatchee and their habitat in the river and estuary (ex. nutrients and stagnation contributing to toxic algae blooms or flows triggering tape grass die offs, both which impact manatees).	The resource-based approach utilizes all available data available for ecological indicators and listed species (threatened or endangered) within the CRE. Many of the other listed species either have insufficient or minimal data available and a scientific analysis is not possible because the species are too mobile in order to have any statistical significance/relevance, or may not serve as a good ecological indicator for reevaluating the MFL. A number of listed species are believed to, or are known to, utilize the open waters and wetlands of the CRE MFL Watershed. Of those species listed, only fish were considered suitable indicators of flow in our resource-based approach. Three listed fish species occur in the CRE; smalltooth sawfish (*Pristis pectinate*), gulf sturgeon (*Acipenser oxyrinchus desotoi*), and mangrove rivulus (*Kryptolebias marmoratus*). The smalltooth sawfish was included as an indicator species in the District's resource-based approach, as discussed in Component Study 11. While the gulf sturgeon is listed as threatened by both the Florida Fish and Wildlife Conservation Commission (FWC) and the U.S. Fish and Wildlife Service (USFWS), there is some disagreement between the two agencies as to the species' range in Florida. USFWS includes the species in Lee County and specifically in the Caloosahatchee National Wildlife Refuge, while FWC indicates the species only occurs in North Florida, from the Suwanee River Basin north. The mangrove rivulus is listed as a species of special concern by FWC. It is not listed by USFWS. According to the FWC, the mangrove rivulus inhabits mangrove forests and it is an amphibious/fossorial species (it is capable of living on land and water, and it burrowers on land). Most of its time is spent on land where it can be found hidden in rotten wet logs or under moist leaf litter (Taylor et al. 2008). Therefore, this species was not considered a suitable indicator of flow. Reference: Taylor, D.S., B.J. Turner, W.P. Davis, and B.B. Chapman. 2008. A novel terrestrial fish habitat inside emergent logs. *American Naturalist* 171(2):263-266.
10/14/16	CSWF – Letter	Component 7. The point made by the Sanibel-Captiva Conservation Foundation (SCCF) that tape grass coverage can be	Since monitoring began in 1998, investigators were careful to locate restorative plantings away from monitoring sites so there is no direct effect on

Date	Entity	Comment	Response
		increasing due to aggressive replanting efforts rather than by improved salinity conditions alone is valid and should be addressed to determine how much it could have influenced the results of the study.	monitoring results. Restorative planting may influence monitoring sites by supplying seeds. This may enhance the rate of recovery when salinity and light conditions are favorable. Identifying stressful conditions is relevant to the MFL. In addition, there is no evidence that restorative plantings have served as a seed source to monitoring sites in the estuary. No restorative planting has established a permanent tape grass bed. Like native populations, transplants have died when conditions become stressful.
10/14/16	CSWF – Letter	Components 7 and 8. We support SCCF's recommendation that the SFWMD analyze the 30 year moving averages instead of the annual averages because real world data shows that 650 cfs flow is often insufficient to attain and maintain the 10 psu target.	See previous comments and **Attachment A-2**.
10/14/16	CSWF – Letter	Components 7 and 8. Since significant harm has already occurred, it would be appropriate to set the MFL at conditions that promote restoration and the recovery of these resources, rather than to just prevent further significant harm.	Section 373.042, F.S., sets the standard for setting MFLs.

ATTACHMENT A-2: SALINITY AT FT. MYERS MONITORING STATION AND FRESHWATER INFLOW TO THE CRE

Peter Doering and Fawen Zheng

Introduction

The current MFL rule for the CRE was adopted in 2001. The rule has two salinity thresholds. The first is a 30-day moving average salinity of 10, measured at the surface sensor of the monitoring station located in the Ft. Myers Yacht Basin. The second is a daily average salinity of 20 measured at the same location. The salinity value of 10 is based on the salinity tolerance of tape grass (*Vallisneria americana*). It is generally agreed in the literature that a salinity of 10 or below is required for a sustainable population (French and Moore 2003). The District's work supports this conclusion (Doering et al. 2002). Calculating the amount of freshwater inflow required to produce a surface salinity of 10 at Ft. Myers is an important step in evaluating the current MFL.

Surface water inflow to the CRE is primarily delivered at the Franklin Lock and Dam (82% of total). Additional flows enter the estuary from the Tidal Basin (18 % of total) downstream of S-79.

There are various ways to estimate the amount of freshwater inflow required to produce a salinity of 10 at Ft. Myers. Buzzelli (2016) regressed mean monthly flow at S-79 (x) on mean monthly salinity (y) at Ft. Myers for the water years 1993 through 2012. The relationship between discharge at S-79 and salinity at Ft. Myers could be described by a negative exponential relationship. Considering all months (n=256) the regression explained 82% of the variability and suggested that a mean monthly flow of 485 cfs at S-79 would produce a mean monthly salinity of 10 at Ft. Myers. Examination of individual water years indicated that this value was not constant but varied on an annual basis from 70 to 773 cfs and averaged (± standard deviation) 445 ± 218 cfs. Bartleson (personal communication) regressed the 30-day moving average salinity at Ft. Myers (y) on the 30-day moving average flow at S-79 (x) using a negative exponential model. The regression explained 81% of the variability in salinity and estimated that 620 cfs were necessary to produce a salinity of 10 at Ft. Myers. Considering the 95% confidence bounds on the regression coefficients the range was 597 to 649 cfs. Here we examine the relationship between daily average inflow and daily average salinity at Ft. Myers.

Methods

Flow at S-79 and salinity at the Ft. Myers monitoring station were downloaded from the District's data base DBHYDRO. The period of record (POR) covered the period May 1, 1996 through April 30, 2016. The data set was the same used in Chapter 8C of the *2017 South Florida Environmental Report* (Zheng et al. 2017). Rainfall for the Tidal Basin was also available from DBHYRO. These data were used to predict Tidal Basin inflow (May 1, 1996–May 31, 2014) using a linear reservoir model Wan and Konyha (2015).

Daily flow and salinity data were sorted by date and further classified according to season (wet season is May–October; dry season is April–November). A negative exponential model was fit to the data using the SAS version 9.3 procedure Proc NLIN. The model was as follows:

$$\text{Surface Salinity} = \text{Beta0} * e^{(-\text{Beta1}*\text{Flow})} \qquad \textbf{\textit{A-2.1}}$$

where

Salinity was average daily salinity for a given day

Flow was average daily flow on that day in cfs

Separate regressions were computed for flow at S-79 and for total flow (S-79 + Tidal Basin). Overall and seasonal regressions (wet and dry) were also computed. To determine the flow that produces a salinity of 10 at Ft. Myers, the above equation was solved for flow assuming a salinity of 10. Proc NLIN provides the approximate upper and lower limits of the 95% confidence bands for Beta0 and Beta1. Again, by solving the above equation for flow assuming a salinity of 10, these limits were used to estimate a potential range of flows that could result in a salinity of 10. It is important to note that if Beta0 is less than 10, a negative value for inflow results if the equation is rearranged and solved for a salinity of 10.

Results and Discussion

Over the POR (May 1, 1996–April 30, 2016), daily surface salinity at Ft Myers averaged 6.8 ± 6.9 (**Table A-2-1**). Flow at S-79 (1,971 ± 2,713 cfs) was nearly four times the Tidal Basin inflow. In estuaries, patterns of salinity and flow are generally inverse. When flow is low salinity is high. Flow in the wet season was higher than in the dry season and, as expected, salinity was lower in the wet season and higher in the dry season.

Table A-2-1. Mean surface salinity at Ft. Myers, discharge at S-79 (cfs) and Tidal Basin inflow (cfs) calculated seasonally (dry, wet) and using all the data (overall) for May 1, 1996–April 30, 2016). (Note: Mean, standard deviation [SD], and number of observations [n] are given.)

	All			Dry			Wet		
	Mean	**SD**	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**	**n**
Surface Salinity	6.8	6.9	6,618	8.8	6.8	3,323	4.8	6.5	3,295
S-79 Flow	1,971	2,713	7,305	1,321	2,141	3,625	2,611	3,045	3,680
Tidal Basin Flow	510	626	6,605	241	336	3,262	774	724	3,343

Using all the data, flows at S-79 associated with a salinity of 10 at Ft. Myers averaged 405.8 cfs (**Table A-2-2** and **Figure A-2-1**). Based on the 95% confidence limits for the two parameters of the exponential decay equation (**Equation A-2.1**), flows could range from 373.2 cfs to 446.9 cfs. Dry season flows averaged 495 cfs, with a range of 446.3 to 557.8 cfs. Wet season flow at S-79 estimated to produce a salinity of 10 at Ft. Myers were considerably lower (range: 243.7–349.4 cfs).

Table A-2-2. Relationship of Salinity at Ft. Myers to discharge at S-79 for May 1, 1996–April 30, 2016. (Notes: Estimates of the exponential decay coefficients, Beta0 and Beta1, are from non-linear regression. Also given are the approximate 95% confidence limits for these estimates and the calculated flows at S-79 resulting in a Salinity of 10 at Ft. Myers.)

S-79		95% L	Estimate	95% U	R^2	n
All Data	Beta0	13.8	14.0	14.2	0.526	6618
	Beta1	-0.00086	-0.00083	-0.00079		
	Flow (cfs) for S_{10}	373.2	405.8	446.9		
Dry Season	Beta0	14.2	14.4	14.7	0.521	3323
	Beta1	-0.00078	-0.00089	-0.00083		
	Flow (cfs) for S_{10}	446.3	495.0	557.8		
Wet Season	Beta0	12.6	13.0	13.4	0.457	3295
	Beta1	-0.00094	-0.00089	-0.00083		
	Flow (cfs) for S_{10}	243.7	292.6	349.4		

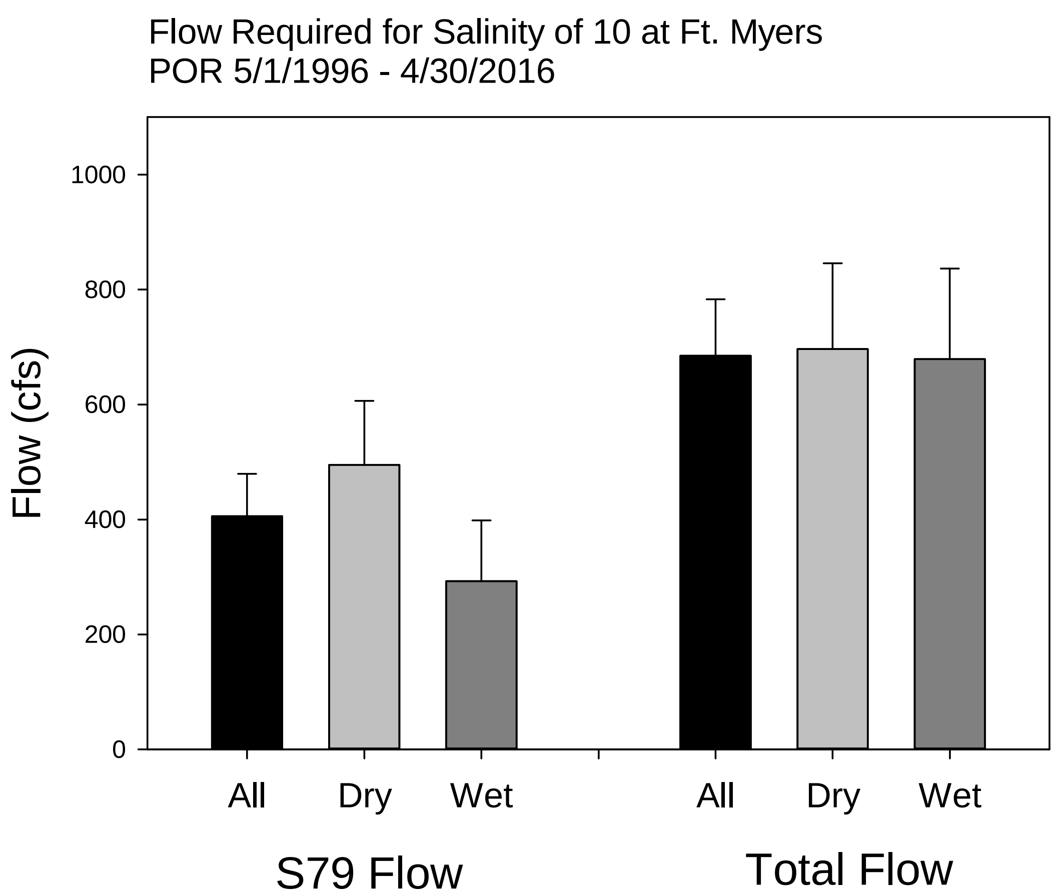

Figure A-2-1. Daily average flow required to produce a daily average surface salinity of 10 at the Ft. Myers monitoring station for May 1, 1996–April 30, 2016. (Note: Calculations [± 95% Confidence Range] are given for entire POR, wet and dry seasons and for flow at S-79, and total flow [S-79 + Tidal Basin].)

Estimates of total flows (S-79 + Tidal Basin) associated with a salinity of 10 at Ft. Myers were remarkably similar. Average estimates for the wet season, dry season, and all the data were within 20 cfs of each other (**Table A-2-3**). This result contrasts with the large wet season/dry season difference for flows at S-79 (**Table A-2-2**). It suggests (1) that the total inflow required to produce a salinity of 10 at Ft Myers varies far less than the flow required from S-79; and (2) much of the seasonal variation in required flow at S-79 is due to seasonal differences in Tidal Basin inflow.

Table A-2-3. Relationship of salinity at Ft. Myers to total inflow (S-79 + Tidal Basin) for May 1, 1996–May 31, 2014. (Notes: Estimates of the exponential decay coefficients, Beta0 and Beta1, are from non-linear regression. Also given are the approximate 95% confidence limits for these estimates and the calculated flows at S-79 resulting in a salinity of 10 at Ft. Myers.)

Total Inflow		95% L	Estimate	95% U	R^2	n
All Data	Beta0	15.8	16.0	16.3	0.576	5917
	Beta1	-0.00072	-0.00069	-0.00067		
	Flow (cfs) for S_{10}	632.7	685.0	730.6		
Dry Season	Beta0	15.5	15.8	16.2	0.505	2960
	Beta1	-0.0007	-0.00066	-0.00062		
	Flow (cfs) for S_{10}	625.9	696.5	775.4		
Wet Season	Beta0	15.9	16.4	16.919	0.555	2958
	Beta1	-0.00077	-0.00073	-0.00069		
	Flow (cfs) for S_{10}	604.1	679.1	761.5		

The magnitude of the daily flows at S-79 required to produce a salinity of 10 at Ft. Myers (373.2–446.9 cfs) are within the same range of mean monthly flows calculated by Buzzelli (2016; 70–773 cfs) and the mean estimates (405.7 cfs for average daily and 445 cfs for mean monthly) are quite close, differing by only 9.6% relative to the daily average.

The POR chosen for analysis also appears to influence estimates of the flow required to produce a salinity of 10 at Ft. Myers. The analyses above were repeated for a POR of June 29, 2000–October 19, 2014 (**Tables A-2-4** and **A-2-5** and **Figure A-2-2**). These correspond to that employed by Bartleson (personal communication). Comparison of **Tables A-2-1** and **A-2-4** and **Figures A-2-1** and **A-2-2** reveals that estimates based on the June 29, 2000–October 19, 2014, POR are generally higher than those based on the longer POR (May 1, 1996–May 31, 2014). This difference may at least in part be due to interannual variation in the salinity-flow relationship similar to that observed by Buzzelli (2016). An example of such variation is given in **Figure A-2-3**, which compares the daily average salinity/flow relationships for WY2000 and WY2009. Note that in WY2009, the estimated flow required to produce a salinity of 10 at Ft. Myers was over twice that estimated in WY2000.

Table A-2-4. Relationship of Salinity at Ft. Myers to discharge at S-79 for June 29, 2000–October 19, 2014. (Notes: Estimates of the exponential decay coefficients, Beta0 and Beta1, are from non-linear regression. Also given are the approximate 95% confidence limits for these estimates and the calculated flows at S-79 resulting in a salinity of 10 at Ft. Myers.)

S-79		95% L	Estimate	95%U	R^2	n
All Data	Beta0	15.00	15.27	15.55	0.556	4359
	Beta1	-0.00088	-0.00084	-0.0008		
	Flow (cfs) for S_{10}	460.28	503.44	551.33		
Dry Season	Beta0	14.66	15.00	15.33	0.455	2235
	Beta1	-0.0008	-0.00075	-0.00069		
	Flow (cfs) for S_{10}	477.65	540.07	618.57		
Wet Season	Beta0	15.34	15.83	16.32	0.557	2304
	Beta1	-0.00103	-0.00097	-0.0009		
	Flow (cfs) for S_{10}	415.01	473.10	543.77		

Table A-2-5. Relationship of salinity at Ft. Myers to total inflow (S-79 + Tidal Basin) for June 29, 2000–October 19, 2014. (Notes: Estimates of the exponential decay coefficients, Beta0 and Beta1, are from non-linear regression. Also given are the approximate 95% confidence limits for these estimates and the calculated flows at S-79 resulting in a Salinity of 10 at Ft. Myers.)

Total Inflow		95% L	Estimate	95%U	R^2	n
All Data	Beta0	16.92	17.25	17.58	0.601	4398
	Beta1	-0.00077	-0.00073	-0.0007		
	Flow (cfs) for S_{10}	682.46	746.32	805.37		
Dry Season	Beta0	16.07	16.48	16.89	0.474	2235
	Beta1	-0.00076	-0.00071	-0.00066		
	Flow (cfs) for S_{10}	623.62	703.02	793.52		
Wet Season	Beta0	18.99	19.57	20.15	0.654	2163
	Beta1	-0.00085	-0.00081	-0.00076		
	Flow (cfs) for S_{10}	754.01	828.39	921.32		

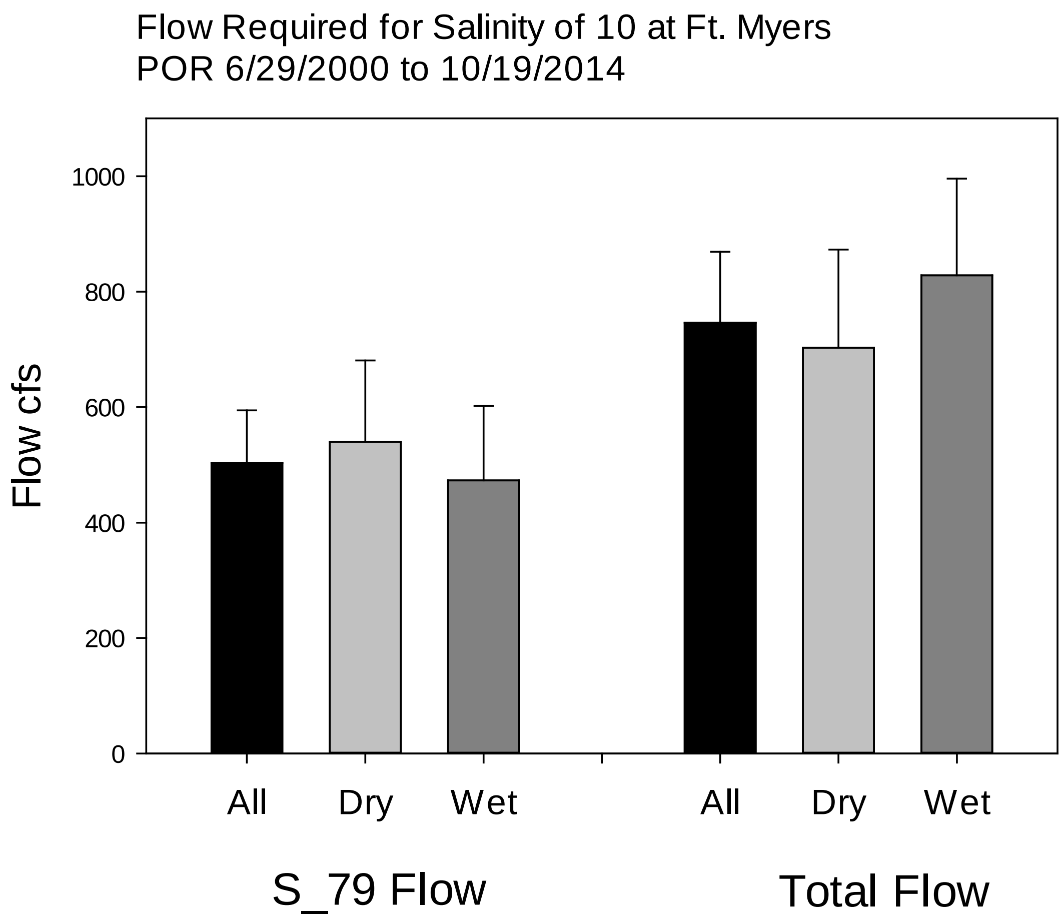

Figure A-2-2. Daily average flow required to produce a daily average surface salinity of 10 at the Ft. Myers monitoring station for June 29, 2000–October 19, 2014. (Note: Calculations [+ 95% Confidence Range] are given for entire POR, wet and dry seasons, from flow at S-79, and total flow [S-79 + Tidal Basin].)

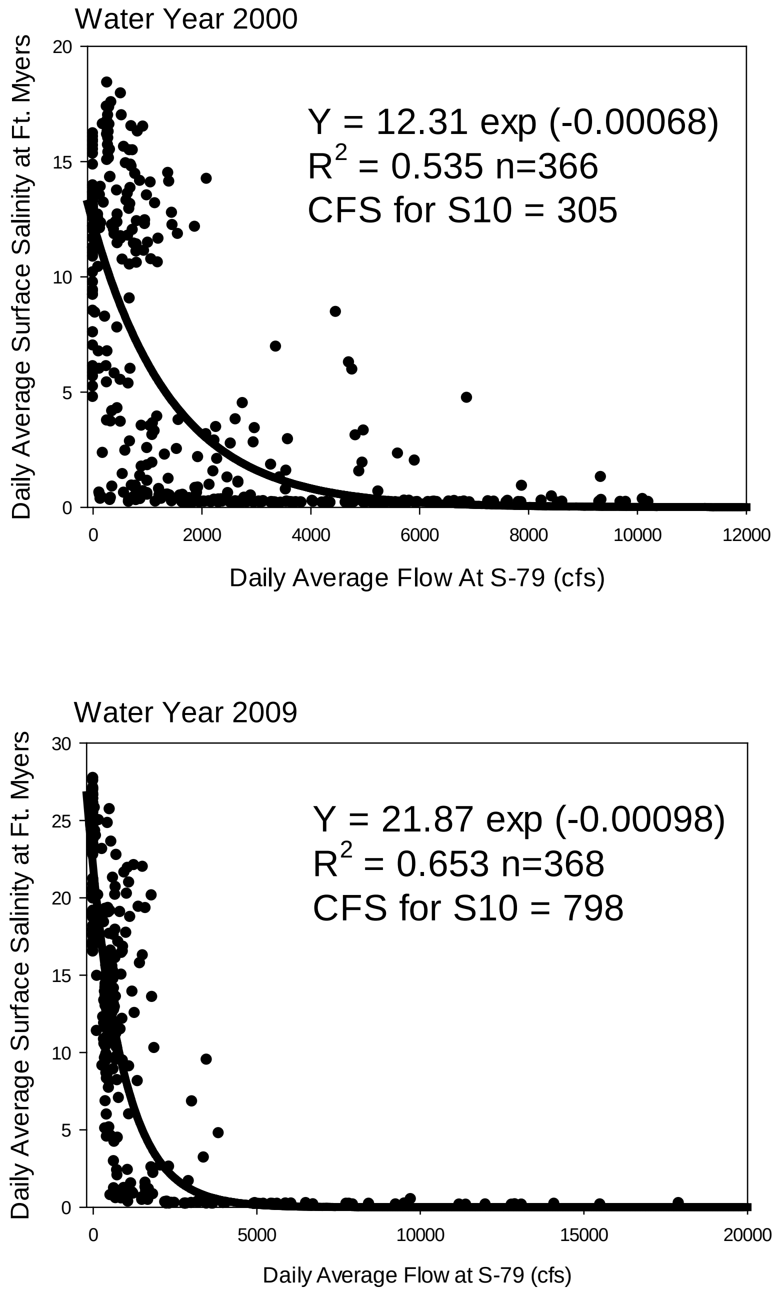

Figure A-2-3. Daily average flow at S-79 and daily average surface salinity at Ft. Myers in WY2000 (May 1, 1999–April 30, 2000) and WY2009 (May 1, 2008–April 30, 2009). Also given is the flow at S-79 required to produce a salinity of 10 at Ft. Myers.

Comparison of the All Data category results in **Table A-2-4** with those of Bartleson indicates that the way both salinity and flow are averaged influences results. The flows producing 10 at Ft. Myers estimated by Bartleson using 30-day moving averages of both variables ranged from 597 to 649 cfs. Estimates based on daily averages used in this report were lower, ranging from 460 to 551 cfs.

We repeated Bartleson's analysis, regressing the 30-day average surface salinity at Ft. Myers on the 30-day average flow at S-79. In order for our estimates of flows resulting in a salinity of 10 to come close to Bartleson's, we had to eliminate flows greater than 4,000 cfs from the analysis (**Table A-2-6**). Even then, our results were substantially lower than his.

Lastly, rather than rearranging the equation relating flow (x) to salinity (y) to estimate a flow associated with a salinity of 10, a regression of salinity (x) on flow (y) may be derived and the flow calculated directly. Palmer et al (2015) used a 2- parameter exponential decrease model:

$$\mathrm{Ln}(Q+1)=ae^{-bS} \qquad \textbf{\textit{A}-2.2}$$

where

Q is flow at S-79

S is salinity

When such an approach was employed in the present case, estimates of the flow producing a salinity of 10 at Ft. Myers appeared low (e.g. 87 cfs for all the data) and unreasonable.

Table A-2-6. Negative exponential relationships between 30-day moving average salinity at Ft. Myers and 30-day moving average discharge at S-79. (Notes: Calculations were made for two different time periods using all data or just dry season data. Also, the case where very high flows [> 4,000 cfs] were eliminated from the analysis was investigated.)

POR	All Seasons Flow			All Seasons Flow < 4,000 cfs		
	R^2	Equation	Q for S_{10}	R^2	Equation	Q for S_{10}
5/1/1996–4/30/2016	0.649	$y=9.244e^{-0.000561x}$	~ 0 [a]	0.703	$y=17.184e^{-0.00113x}$	479
6/29/2000–10/29/2014	0.726	$y=10.475e^{-0.000565x}$	82	0.703	$y=17.597e^{-0.00112x}$	505

POR	Dry Season Flow			Dry Season Flow < 4,000 cfs		
	R^2	Equation	Q for S_{10}	R^2	Equation	Q for S_{10}
5/1/1996–4/30/2016	0.757	$y=11.246e^{-0.000596x}$	197	0.836	$y=17.184e^{-0.00113x}$	479
6/29/2000–10/29/2014	0.73	$y=12.441e^{-0.000674x}$	324	0.861	$y=18.119e^{-0.00118x}$	504

a. Too many high flows prevent obtaining a reasonable Q in this case.

Conclusion

The relationship between flow (x) and salinity (y) was modeled using a two parameter negative exponential equation. Estimates of the flow required to produce a salinity of 10 at Ft. Myers depended on the POR selected for analysis and methods used to preprocess the data (averaging periods) prior to regression. Results presented here corroborate the observations of Buzzelli (2016) who found considerable interannual variation in the relationship between flow at S-79 (x) and salinity at Ft. Myers (y). Two points relevant to establishing a minimum flow at S-79 may be made. First, using a regression approach to estimate a minimum flow based on salinity will not produce consistent results unless the POR is consistent and the data are consistent (e.g. daily average or monthly average). Secondly, because of interannual variation in the flow-salinity relationship, a flow at S-79 estimated from data spanning multiple years will not consistently produce a salinity of 10 at Ft. Myers.

Literature Cited

Buzzelli, C. 2016. Component Study 2: Analysis of the relationship between freshwater inflow at S-79 and salinity in the Caloosahatchee River Estuary 1993-2013. In: Buzzelli et al 2016. *Assessment of the responses of the Caloosahatchee River Estuary to low freshwater in flow in the dry season*. South Florida Water Management District.

Doering, P.H., R.H. Chamberlain, and D. Haunert. 2002. Using submersed aquatic vegetation to establish minimum and maximum freshwater inflows to the Caloosahatchee Estuary, Florida. *Estuaries* 25:1343-1354.

French, GT and K.A. Moore. 2003. Interactive effects of light and salinity stress on the growth, reproduction, and photosynthetic capabilities of *Vallisneria americana* (wild celery). *Estuaries* 26(5):1255-1268.

Palmer, T.A., P.A. Montagna, R.H. Chamberlain, P.H. Doering, Y. Wan, K.M. Haunert and D.J. Crean. 2015. Determining the effects of freshwater inflow on benthic macrofauna in the Caloosahatchee Estuary, Florida. *Integrated Environmental Assessment and Management* 12(3):529-39, doi:10.1002/ieam.1688.

Wan, Y. and K. Konyha. 2015. A simple hydrologic model for rapid prediction of runoff from ungauged coastal catchments. *Journal of Hydrology* 528:571-583.

Zheng, F., P. Doering, Z. Chen, L. Baldwin, B. Orlando, R. Robbins and B. Welch. 2017. Chapter 8C: St. Lucie and Caloosahatchee River Watershed Research and Water Quality Monitoring Results and Activities. In: *2017 South Florida Environmental Report – Volume I*. South Florida Water Management District, West Palm Beach, FL.

Related Correspondence

On Monday, September 19, 2016, at 7:46 AM, Peter Doering <pdoering@sfwmd.gov> wrote the following:

Hi Rae Ann,

As always it was nice to see you and to talk with you at the Caloosahatchee MFL Science Symposium last week.

During discussions, it became apparent that there was not general agreement on estimates of the discharge at S-79 that produces a surface salinity of 10 at the District's monitoring station at the Ft. Myers yacht basin. It seems estimates that SCCF [Sanibel-Captiva Conservation Foundation] is making may not agree with those that we presented during the symposium. During the question and answer period we asked that SCCF send us an analysis describing how estimates of the relationship between flow and salinity are being made and how the calculation of the discharge at S-79 required to produce a salinity 10 at Ft Myers is conducted. We would very much like to work with SCCF to understand the technical basis for any differences.

Please send us the details of the SCCF analysis, including the raw data and source of the data that were used. We would be happy to provide you more details of the analysis we presented at the symposium if you would like.

Best,

Peter Doering
Coastal Ecosystems Administrator
Applied Sciences Bureau
South Florida Water Management District
3301 Gun Club Road
West Palm Beach, FL 33406
561-682-2772
pdoering@sfwmd

From: Rick Bartelson rbartleson@sccf.org
Sent: Thursday, September 22, 2016 12:22 PM
To: Doering, Peter
Cc: Eric Milbrandt: Rae Ann Wessel
Subject: Re: Fort Myers yacht basin 30dma salinity and flow 2000-2014
Attachments: S79Flow30dmavs30dmasalFtMyYachtbasin2000-20014.pdf

Hi Peter,

I've calculated the S79 flow vs Fort Myers yacht basin salinity using DBHYDRO data several ways. The attached document shows one way- using 30 day averages, that Steve Schubert asked for a while back. We'll send you some other estimations shortly.

Richard Bartleson, Ph.D
Research Scientist
SCCF Marine Lab
239 395 4617

On Thursday, September 22, 2016, at 12:31 PM, Peter Doering <pdoering@sfwmd.gov> wrote the following:

Hi Rick,

Thanks for sending. Would you have any additional statistics from the regression analysis? The 95% confidence limits on the estimates would be useful in assessing errors.

Thanks,

Peter

Peter Doering
Coastal Ecosystems Administrator
Applied Sciences Bureau
South Florida Water Management District
3301 Gun Club Road
West Palm Beach, FL 33406
561-682-2772
pdoering@sfwmd.gov

From:	Rick Bartelson rbartleson@sccf.org
Sent:	Thursday, September 22, 2016 5:40 PM
To:	Doering, Peter
Subject:	Re: Fort Myers yacht basin 30dma salinity and flow 2000-2014
Attachments:	S79Flow30dmavs30dmasalFtMyYachtbasin2000-20014.pdf

Hi Peter,

I included the confidence intervals on this copy. Which I hope helps. And I'll include those details with my other graphs tomorrow.

Rick

This is an exponential curve-fit of SFWMD Fort Myers Yacht Basin 30 day average surface salinity and the 30 day average flows at S-79 from 6/29/2000 to 10/19/2014 (periods when data were available). Salinity= 20.7 exp $^{(-0.0011 \text{ x Flow})}$. The R^2 is 0.81. The regression equation calculates 10 psu at 620 cfs. (Source of raw data: DBHYDRO, FortmyersM daily average conductivity25 and temperature, UNESCO[4] calculation of salinity from conductivity (corrected from C_{25}) and temperature and S79 Flow. 95% confidence intervals: y(Salinity)=20.41 to 20.94, K=0.001137 to 0.001194.

[4] UNESCO – United Nations Educational, Scientific and Cultural Organization.

APPENDIX B: SUMMARY OF PEER REVIEW AND PUBLIC COMMENTS AND RESPONSES ON THE *DRAFT TECHNICAL DOCUMENT TO SUPPORT REEVALUATION OF THE MINIMUM FLOW CRITERIA FOR THE CALOOSAHATCHEE RIVER ESTUARY*

This appendix provides the reader with a summary of comments received from an independent scientific peer review panel and the public before, during, and after the public Caloosahatchee Peer Review Session held in Fort Myers on August 17, 2017 (agenda attached). The primary objective of the public Peer Review Session was to receive and respond to comments and questions from the peer review panel on the technical methods and scientific approaches employed by the South Florida Water Management District (SFWMD or District) to determine the revised minimum flows and minimum water levels (MFL) criteria and receive technical feedback on the *Technical Document to Support Reevaluation of the Minimum Flow Criteria for the Caloosahatchee River Estuary* (draft report dated July 2017). In accordance with Section 373.042(5), Florida Statutes, this technical document contains all of the science, final data, methodologies, and models, including all of the scientific and technical assumptions employed in each model upon which the minimum flow is based.

A secondary objective was to ensure an understanding of the technical guidance provided by the panel to the District and hear public comments/concerns about the MFL reevaluation and draft technical document. All verbal and written comments received before, during, and after the public peer review session were reviewed by SFWMD, and where appropriate, they were addressed in the final version of the technical document.

Schedule of Caloosahatchee Peer Review Session

August 17, 2017

South Florida Water Management District/Fort Myers Service Center
1st Floor Conference Room, 2301 McGregor Boulevard, Fort Myers, FL 33901

9:00 AM – 9:15 AM	Introductions and Objectives
9:15 AM – 10:30 AM	SFWMD Presentations · Minimum Flow and Minimum Water Level (MFL) Overview (Don Medellin) · Overview of Approach to Develop MFL Criteria (Chris Buzzelli) · Modeling Approach (Jenifer Barnes, Fawen Zheng, Detong Sun and Chris Buzzelli)
10:30 AM – 11:00 AM	Peer Review Panel Questions on Presentations
11:00 AM – 11:15 AM	Break
11:15 AM – 12:00 PM	Peer Review Panel Questions and Concerns on Reevaluation and Draft Technical Document
12:00 PM – 12:30 PM	Public Comment
12:30 PM – 2:00 PM	Lunch
2:00 PM – 2:05 PM	Format for Afternoon Session
2:05 PM – 4:00 PM	Collaborative Peer Review Panel Discussion · Development of Final Peer Review Report Outline and Writing Assignments · Development of Outstanding Questions for SFWMD
4:00 PM – 4:15 PM	Break
4:15 PM – 5:00 PM	Public Comment
5:00 PM – 5:15 PM	Wrap Up and Next Steps
5:15 PM	Adjourn

THIS SESSION IS OPEN TO THE PUBLIC. THE DRAFT TECHNICAL DOCUMENT IS AVAILABLE AT https://www.sfwmd.gov/our-work/mfl UNDER *NEW PUBLIC PEER REVIEW SESSION FOR THE CALOOSAHATCHEE MFL REEVALUATION*. COMMENTS ON THE DRAFT TECHNICAL DOCUMENT ARE REQUESTED TO BE SUBMITTED BY SEPTEMBER 01, 2017 TO: Toni Edwards, Senior Scientist, South Florida Water Management District, P.O. Box 24680, West Palm Beach, FL 33406; (800) 432-2045, ext. 6387; (561) 682-6387; tedwards@sfwmd.gov.

PEER REVIEW PANEL VERBAL AND WRITTEN COMMENTS ON DRAFT TECHNICAL DOCUMENT AND MFL REEVALUATION

Comment Number	Date	Entity	Comment	Response
Draft Technical Document				
1A	8/2/17	Peer Review Panel Written Reviews	Document is excessively long and repetitive.	There is some repetitiveness in the supporting MFL Technical Document (SFWMD 2017) in part because the Science Summary (Buzzelli et al. 2017), which is Appendix A of the Technical Document, was completed first. Additionally, more detailed information regarding changes and structural alterations within the watershed are also provided in the supporting MFL Technical Document. Specific guidance to reduce repetitive text and graphics along with modifications to other tables and figures will be considered before the Technical Document is finalized.
1B	8/17/17	Dr. Pinckney, Peer Review Panel	I understand why the draft Technical Document was assembled as it was. It can probably be reduced in size. The same graph or table was seen three or four times.	
2	8/2/17	Peer Review Panel Written Reviews	Need more information on the C-43 Reservoir regarding the location, storage provided, and future plans.	The Caloosahatchee (C-43) West Basin Storage Reservoir (C-43 Reservoir), to be located south of the C-43 Canal near Labelle, Florida, is part of the MFL recovery strategy. The storage to be provided is 170,000 ac-ft. *Chapter 10: Existing Recovery Strategy and Evaluation* of the draft Technical Document (SFWMD 2017) is not included because the contents are under development and will also include policy considerations made by the District Governing Board that are outside the scope of this scientific peer review.
Methods and Approaches				
3	8/2/17	Peer Review Panel Written Reviews	The chosen Valued Ecosystem Component (VEC) is heavily dependent on *Vallisneria americana* (tape grass)	District staff evaluated previously collected data (late 1980s, before the MFL was initially established) and new monitoring and modeling data for this reevaluation. All available data using multiple ecological indicators were used as part of this reevaluation.
4	8/2/17	Peer Review Panel Written Reviews	The District should consider a second VEC species such as blue crab population dynamics in the event tape grass does not get reestablished.	The comment is acknowledged.
5	8/2/17	Peer Review Panel Written Reviews	Total suspended solids in light and water quality models	A comprehensive study on light attenuation was done by Chen et al. (2015) where they went up and down the estuary for two years to quantify the constituents. In the upper estuary, color dominates but, in the lower estuary, suspended solids dominate. In a total maximum daily load (TMDL) study, the model showed a 70% contribution of total suspended solides (TSS) to light attenuation in the lower estuary. When the estuary is extremely dry, suspended solids and chlorophyll play a larger role. There has been no change in colored

<table>
<tr><th>Comment Number</th><th>Date</th><th>Entity</th><th>Comment</th><th>Response</th></tr>
<tr><td></td><td></td><td></td><td></td><td>dissolved organic matter (CDOM) since the 1970s. Relevant data have been forwarded to Dr. Lung. Also, see responses to comments 25A, 25B, 25C, 17A, 17B, and 17C.</td></tr>
<tr><td>6A1</td><td>8/2/17</td><td>Peer Review Panel Written Reviews</td><td>There were multiple comments regarding nutrient loads and water quality:

Application of salinity (tidal range, dispersion, etc.)

Hypoxia and CHL

Total maximum daily loads (TMDL)</td><td rowspan="2">Hypoxia and Chlorophyll a (CHL): The District's analysis focused on the dry season and we discovered that lower dissolved oxygen (DO) in the upper estuary, from S-79 to 12 kilometers (km) downstream, occurs in the deepest part of the estuary that has been dredged and channelized. During extreme dry periods, the residence time may approach two months and the salt wedge moves up the narrows above Beautiful Island and becomes stratified. During that time, phytoplankton production occurs in the upper water column and low oxygen (hypoxia) occurs in the lower water column. Due to the limited data taken during the dry season, the dynamics are not fully understood.

Nutrient Loads and Water Quality: The focus of the MFL reevaluation was to determine the minimum flow needed for all indicators to prevent significant harm (Section 373.042, F.S.). There is a separate statewide TMDL program implemented by the Florida Department of Environmental Protection (FDEP), which identifies waterbodies throughout the state that are not currently meeting applicable state water quality standards, establishes a specific TMDL for each waterbody identified, and implements pollution reduction strategies. See this link for more information: https://floridadep.gov/dear/water-quality-evaluation-tmdl/content/total-maximum-daily-loads-tmdl-program

The TMDL for the Caloosahatchee River Estuary (CRE) is in the process of being reevaluated. Previously the TMDL was based on a light attenuation coefficient type target in San Carlos Bay and predicated on the idea that you could reduce nutrient loading with reduced CHL, which translates to better light penetration and better seagrass.

The District is coordinating with FDEP to evaluate the water quality model with both 300 and 400 cfs.</td></tr>
<tr><td>6A2</td><td>8/17/17</td><td>Dr. Pinckney, Peer Review Panel</td><td>For the TMDLs FDEP is developing, are they assuming a 400 cfs or are they going by the historical 300 cfs?</td></tr>
<tr><td>6B</td><td>8/17/17</td><td>Dr. Lung, Peer Review Panel</td><td>Perhaps you could take advantage of the state TMDL effort and see what they come out with first.</td><td>FDEP had challenges with their simulations for the CRE because their light model was not specifically formulated for the estuary and the role of CDOM in light attenuation. FDEP is working with their contractors to reformulate their light model. The District has reviewed and presented written comments on FDEP TMDL modeling including other aspects of the water quality modeling and continues to coordinate with FDEP on these issues.</td></tr>
</table>

Comment Number	Date	Entity	Comment	Response
6C	8/17/17	Dr. Pinckney, Peer Review Panel	Are there any data on long term trends in CDOM? Is it increasing, is it relatively constant?	District staff performed an analysis of CDOM trends last year using data from the S-79 structure and the results indicated there has been no change in CDOM since the 1970s.
6D	8/17/17	Dr. Shen, Peer Review Panel	Chlorophyll is really dependent on residence time. If you have increased residence time, it will cause a bloom. If you increase flow, it can increase nutrients. If flow is not too high, stratification can occur in deep pockets. Gravitational circulation can bring nutrients to these deep pockets. Under these conditions, water doesn't move much, it is steady and vertical mixing is reduced, which can cause dissolved oxygen (DO) [decline]. It might be important to define the cause, what is the created condition? Low flow is a critical condition for DO, but it is not the only factor contributing to low DO.	We agree. In the upper part of the CRE, low flow increases the residence time and improves light conditions. The possibility of stratification may also play a role in creating a low DO condition.
6E	8/17/17	Dr. Lung, Peer Review Panel	The low DO is usually in the lower estuary right?	Monthly monitoring (grab sample data) certainly shows that low DO, less than 4, occurs in the upper estuary during warmer times of the year. See Doering et al. (2006).
7	8/2/17	Peer Review Panel Written Reviews	Why wasn't a wetland indicator used in the evaluation of VECs?	There are very few wetland habitats along the CRE due to previous alterations and existing residential developments along the shoreline.
8	8/2/17	Peer Review Panel Written Reviews	Describe why each indicator is suitable as a sentinel species for this effort (e.g., why was ichthyoplankton used versus juvenile fish?).	Data from the late 1980s and more recent data on indicator species were analyzed as part of this reevaluation. The major components that comprise icthyoplankton were evaluated. The majority of the icthyoplankton did not respond to flow or salinity. Ichthyoplankton species were found mainly in the lower estuary. Juvenile fish data indicated a sensitivity of juvenile fish to salinity. Juveniles were found mainly in the upper estuary. Their specific location in the estuary changed based on flow ranges. That is why juvenile fish became the indicator in the reevaluation as opposed to icthyoplankton.
9	8/2/17	Peer Review Panel Written Reviews	Consider a weighed approach for ecological indicators	The comment is acknowledged.
10	8/17/17	Dr. Buskey, Peer Review Panel	It seemed like all of the other components mainly contributed to understanding the magnitude of flow that was necessary, and only two of them really related to duration. It would be nice to have a little more support for the duration.	We agree. The water column is a complex place, and the organisms that live in the water column can be quite complicated as well. If we had another indicator, particularly a benthic indicator, that would be helpful.

Comment Number	Date	Entity	Comment	Response
11	8/17/17	Dr. Pollack, Peer Review Panel	It wasn't clear in the writing that there were two different life stages involved in the analysis, particularly in the figure that shows the different indicator flows. Also, was there a particular method used to identify indicator species or indicator communities? Sometimes within those communities there are one or two species that are going to be better indicators, rather than looking at the whole suite of organisms.	The flow indicator is based on juvenile fish, primarily *Anchoa mitchelli*, and this is not explicitly stated in the Summary section. It is only made clear in the appendix.
Data and Information				
12A	8/2/17	Peer Review Panel Written Reviews	Potential problems of salinity averaging (day, month, season). Why was only surface salinity considered for flow scenarios?	Salinity averaging is dictated by the way the rules are constructed (surface versus bottom) and the lack of data on vertical salinity patterns. Monitoring data at 20% of the depth of the water column is used to measure surface salinity for MFL compliance. This depth was chosen because this was the approximate depth at which *Vallisneria americana* (tape grass) was found when the original MFL criteria were developed. The current MFL rule specifies surface monitoring, but the newly proposed criteria do not. The exact measuring point for surface salinity will be revised and incorporated into future draft rule language.
12B	8/17/17	Dr. Pinckney, Peer Review Panel	Organisms don't see the average condition, they see the extremes. You can average over a 10-day period, but if you get a spike in salinity, that can cause mortality or damage that you don't see by averaging, especially over long time periods. The other issue was averaging surface and bottom salinities over time, where again you are removing potentially important variability in those variables. It all goes back to your recommendation for the MFL salinity criterion at Fort Myers [salinity monitoring station], that is based on an average for 55 days. Is that surface salinity, is that bottom salinity averaged? Is that surface and bottom salinity averaged? It wasn't clear how that criterion was going to be applied to meet the MFL at Fort Myers.	
13	8/2/17	Peer Review Panel Written Reviews	Salinity time series relative to ecological resources.	The vertical part can be complicated, although it does not stratify much. We already touched on the fact that we have a benthic resource and we are looking at a surface water salinity. As for the other part, averaging in general, as we developed the different science component studies described in the Science Summary (Buzzelli et al. 2017), each component was targeted a different way, with very specific hypotheses and objectives. Most are very course scale assessments, over many years. In that capacity, the District was comfortable averaging salinity at the appropriate resolution. However, on a time scale of days to months, variability is more critical. To partially address this issue, we are starting to plot our various resources versus the interday variance in salinity and the rate at which it changes week to week. The Curvilinear Hydrodynamic Three Dimensional (CH3D) Model can produce salinity at multiple layers anywhere across the modeling domain.

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				However, the challenge is having the data from those locations for verification.
14A1	8/2/17	Peer Review Panel Written Reviews	Scales and variability of salinity (stratification, residence time, dispersion)	Staff have not noticed any salinity stratification at CES04. It is upstream of there, where the depth is so much greater, that we get stratification. The salinity differs, at most, up to 4 or 5, primarily between 20% and 80% depths.
14A2	8/17/17	Dr. Pinckney, Peer Review Panel	In the systems I'm used to working in, there is a clear salinity gradient from surface to bottom. That might not be the case in this system, it may be homogenous 90% of the time. I just don't have a good feel for this system. It's shallow enough, it's probably well mixed. There may only be special scenarios where you get stratification.	
14B	8/17/17	Dr. Pinckney, Peer Review Panel	Another question dealing with the tape grass model, you were looking at surface salinity, and Vallisneria is benthic. What bias might that give to your modeling and your duration and your frequency? Under these flow scenarios, in that section of the river, you might end up with some stratification and actually have fresher surface waters than you have in deeper waters.	The analysis was performed in this fashion because the original MFL was designed as a surface salinity. Again, this is an excellent point. The original MFL was based on salinity measured at the Ft. Myers salinity monitoring station, which is very close to the channel. It has two sensors, a surface sensor and a bottom sensor. The surface sensor is at 20% of the total depth at mean low water, and the bottom sensor is at 80%. *Vallisneria* does not grow very deep in the CRE, typically not deeper than a meter or so. Therefore, we felt that the measurement at 20% of the depth was more reflective of what *Vallisneria* might be experiencing.
14C	8/17/17	Dr. Lung, Peer Review Panel	Let me add something to this. You're talking about low flow, but the majority of tape grass is in the upstream area, close to CES04. Under low flow, salinity stratification, I suspect, is very minimal.	Staff have not noticed any salinity stratification at CES04. It is upstream of there, where the depth is so much greater, that we get stratification. Tape grass grows in a meter of water. All of these comments are relevant and were considered during model set up.
14D	8/17/17	Dr. Shen, Peer Review Panel	You mentioned yesterday [during the boat trip] that you have circulation in the estuary, but this is a long estuary. You have salinity almost all the way to S-79. It's a little bit different estuary.	One of the reviewers was curious about the variance in salinity along the length of the estuary. A longitudinal salinity profile of the CRE during the dry season (May 10, 2001) has been incorporated into the Technical Document (see Figure 5 in Chapter 2). We suspect this profile can be represented by the well-known steady state dispersion equation. This equation can also explain the regression model developed in this technical analysis. It was also used for the box model studies.
15	8/17/17	Dr. Shen, Peer Review Panel	The criterion is 10 in your model results, but model results presented later indicate a salinity up to 13 [Referring to Slide 62 of Presentation which is Table 16 of draft Technical Document].	That is correct. The salinity criterion is 10 at the Ft. Myers monitoring station, but simulation results suggest there are still some high salinity events, defined as salinity at Ft. Myers greater than 10 for 55 or more consecutive days for existing and future conditions and for with and without C-43 reservoir scenarios. But the average salinity and duration for

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				the high salinity events are significantly reduced with an operational C-43 Reservoir.
16	8/2/17	Peer Review Panel Written Reviews	There is no mention of water quality data collected with plankton tows (i.e., temperature, salinity, oxygen data, etc.).	The comment is acknowledged. Those data are available in Tolley et al. (2010) .
Modeling				
17A	8/2/17	Peer Review Panel Written Reviews	Has SFWMD considered using the Environmental Fluid Dynamic Code Model (EFDC) since the Hydrodynamic Salinity Model (CH3D) does not account for sediment transport? Also consider expanding the CH3D model to include TSS, nutrients and dissolved oxygen.	The CH3D model has been our working model for the CRE since 2002, before the TMDL Environmental Fluid Dynamic Code (EFDC) model was available. We are confident in the model output. Comments on expanding the model to include other parameters will be considered in future updates.
17B	8/17/17	Dr. Shen, Peer Review Panel	Many of the models so far, including the EFDC, are for deep estuaries, not shallow estuaries. If you miss all of the benthic [organisms] and microalgae it probably will not work. This is a very unique situation. Future development might have a spatial process added.	The comment is acknowledged.
17C	8/17/17	Dr. Pollack, Peer Review Panel	I know this is beyond the purview of your charge, which is water quantity, but building on Jian Shen's comments, I wonder with more monitoring or working with [FDEP], if there is a way to build into your model in the future the effects of these pulsed vs. trickle flows from the reservoir and impacts on nutrient loads and impacts on potential phytoplankton blooms. It looks like chlorophyll a isn't a large contributor to light attenuation, but once this reservoir is built, it might be worth investigating how the dynamics of water releases could contribute to changes.	These situations can be tested. FDEP is currently using the EFDC model for reevaluating the TMDL. The EFDC model can be used to simulate different flow scenarios. In its current state, the EFDC model it is good at predicting CHL, TSS, or light attenuation but needs some refinements to better predict nutrients.
18A	8/2/17	Peer Review Panel Written Reviews	Segmented water quality model and sediment-water exchanges.	The District has developed the fully linked hydrodynamic water quality model for the St. Lucie River. Unfortunately, we do not have a similar model developed for the CRE. For the CRE, we have been focused on the hydrodynamic component through CH3D, and the FDEP has been focused on the water quality. We developed a segmented simulation model that has three homogenous boxes, each one having a water quality simulation model in it, and seagrasses in the lower end to link inflows at S-79 to our lower estuary resources and it performs quite well. We acknowledge that a fully coupled hydrodynamic water quality model for the CRE that is linked to benthic resources would provide a more comprehensive assessment of the potential range of effects of changing the inflows and low flows.
18B	8/1717	Dr. Pollack, Peer Review Panel	The model that you have available to you and the results of the model are really impressive. It is perhaps just a matter of finding ways to add more information where you can.	

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19	8/2/17	Peer Review Panel Written Reviews	CH3D model to determine magnitude and duration of inflows.	The hydrodynamic model can be used to test flow scenarios, to help verify flow criteria, or even look for a possible range of criteria. But magnitude and duration is determined by the ecological response of the system.
20	8/2/17	Peer Review Panel Written Reviews	Sensitivity analysis/calibration of tape grass model.	This information is in Component Study 8 of the Science Summary (Buzzelli et al. 2017).
21	8/2/17	Peer Review Panel Written Reviews	Effects on sea level rise.	A significant range of sea level rise, from 2.5 to 10 millimeters per year has been tested using the CH3D hydrodynamic model to find its impact on salinity in the next 20 years. The modeling results show that there will be an insignificant change in sea level rise over the next 20 years.
22A	8/2/17	Peer Review Panel Written Reviews	Details on C-43 Reservoir operations relative to meeting the recommended MFL.	Operations are based on the best use of the reservoir via smart operations targeting different regimes conditional on whether the reservoir is empty or full and what time of the year it is (wet or dry season). In the model, only empty release operations were modified from the C-43 Reservoir project implementation report (PIR; USACE and SFWMD 2010) operations, to send the different minimum flows that were analyzed. When the water is available it is delivered to the CRE. In addition, there are regulatory discharges from Lake Okeechobee. When the discharges are high and storage is available, the reservoir can capture some of this volume and store it for later. Operations of the C-43 Reservoir will be optimized to "fine-tune" the future operations to maximize efficiency of the reservoir. The United States Army Corps of Engineers (USACE) occasionally implements pulse releases in its actual operations during low flow conditions. The model was used to test different release schedules (different pulses with the same average flow). We did not find significant differences in daily salinity. The reviewer's question is understood. There is certainly a lag involved between salinity and flow.
22B	8/17/17	Dr. Shen, Peer Review Panel	More clarification needs to be provided on how the reservoir was operated in the model to assess 300 cfs and 400 cfs. If you move water gradually out, there is probably no effect. Once the salinity is pushed downstream, and it will take time, the operation could be different. It would be interesting to know more about the operations. When flow is low, and you're going to release water from the reservoir, are you going to release high [volumes]…and stop it, hold it for a while, or release it gradually? When the flow is low, will you release it a little bit at a time or quickly all at once? The salinity response could be very different.	
23	8/2/17	Peer Review Panel Written Reviews	Consider using control model simulations to establish distribution of salinity along the estuary and MFL criteria.	We agree. It could be useful to do some controlled experiments.
24	8/17/17	Dr. Pinckney, Peer Review Panel	In your tape grass model, you looked at total irradiance, but especially since you're dealing with CDOM, perhaps the more important variable is light quality. So, it may not be total irradiance they are receiving, but it's the photosynthetically important irradiance they would receive. Meaning, you would actually need to have more surface irradiance to get the	To restate the comment, we agree that total light attenuation coefficient is the pararmeter of interest. We discussed this with Dr. Pinckney. It is true that different plants differentially absorb different wavelengths of light, and different wavelengths penetrate differently within and between different waterbodies. We know of one study that determined a single half-saturation coefficient for total light harvesting by *Vallisneria*. This value was

Comment Number	Date	Entity	Comment	Response
			productivity that you see. So that you've really minimized the influence of CDOM.	used in the Tape Grass Model. We know of no studies to determine varying saturation coefficients for variations in submarine light quality.
Conclusions				
25A	8/2/17	Peer Review Panel Written Reviews	Linkages between total suspended solids and light extinction in the water column need to be established.	See the response to Comment 5.
25B	8/17/17	Dr. Lung, Peer Review Panel	What is the relative contribution to light extinction (Kt) from components such as chlorophyll *a*, detritus, the dead body, and inorganic?	CDOM, CHL, and inorganic suspended solids, are the major constituents that are used to define submarine light everywhere. We would need to defer to someone, such as Dr. Pinckney, on the effects of decaying organics on submarine light. The objective of the study that Zhiqiang Chen et al. (2015) did was to define Kt, from S-79 to the offshore boundary, to the Gulf of Mexico. In that study, the contributions of those constituents was quantified. From Peter Doering: I do not know if degradation products from organic matter were included in the turbidity measurement or not. We did not look at TSS specifically. The relative contribution to Kt varies spatially in this system. In the upper part of the estuary, CDOM is the major contributor to light attenuation, and in the lower estuary, it is turbidity, and CHL is somewhere between 10 and 20%. It is not a major contributor.
25C	8/17/17	Dr. Lung, Peer Review Panel	The suspended solids are obviously the component contributing to light extinction. During a boat trip up the estuary this week, you stated that there is no turbidity there, but in my written review, I did show the results of such data [downloaded from DBHydro]. That's why I asked what the relative contribution was.	In the comprehensive study done by Zhiqiang Chen et al. (2015), sampling was conducted up and down the estuary for two years to quantify constituents. The data from that study can be provided to you. There is a lot of resuspension in San Carlos Bay and the lower estuary. The lower estuary is very shallow, there are a lot of boats, and it is often very windy. So, in the lower estuary, suspended solids dominate. Suspended solids are also present in the upper estuary, but they do not contribute largely to light attenuation. Throughout the upper estuary, color dominates. The water in the upper estuary is dark most of the time, except under extremely dry conditions in January and February. When it is extremely dry, suspended solids and CHL become more important. In the lower estuary, suspended solids are much more important. The TMDL study model shows a 70% contribution in the lower estuary, but not in the upper estuary. Relevant data have been forwarded to Dr. Lung.
26	8/2/17	Peer Review Panel Written Reviews	Achieving the recommended MFL is unlikely until the C-43 Reservoir is completed.	The C-43 Reservoir is a major part of the recovery strategy. The recovery strategy provides new water for environmental purposes that is not available now to help meet the MFL criteria. Our modeling staff discussed the operations of the reservoir; it is

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				designed to maximize the efficiency of meeting that flow target at S-79 as much as possible when water is available in the C-43 Reservoir.
27	8/2/17	Peer Review Panel Written Reviews	Monitoring is essential for documenting water management actions, understand biological responses, and tolerance levels for indicators.	We agree. Monitoring is part of this project. The Comprehensive Everglades Restoration Plan (CERP) monitoring plan developed for the C-43 Reservoir project is designed to monitor the best suite of indicators that are indicative of capturing the anticipated hydrologic and ecological changes in the estuary. These indicators include salinity, water quality, oysters, submerged aquatic vegetation (SAV), and fish. There is also an extensive water quality monitoring plan that must be implemented before any surface water from the C-43 Reservoir is released to the receiving waterbody to ensure state water quality standards are met. For more information regarding the water quality monitoring plan see Annex D, Section D.4 of the PIR (USACE and SFWMD 2010) at the following link: http://141.232.10.32/pm/projects/project_docs/pdp_04_c43/final_pir_nov_2010/110010_vol_3_annx_d_pom_mon_plan.pdf
28	8/2/17	Peer Review Panel Written Reviews	Consider monitoring blue crab population dynamics as a future VEC.	It is unlikely that blue crabs can be used as an indicator in the CRE for several reasons. First, there is no historical scientific data on the blue crab life cycle that could be paired with historical fishery (catch) data. Second, this species is very mobile and the life cycle is very complex. Each stage of their life cycle also has specific salinity requirements. Finally, during a portion of most wet seasons, the salinity gradient in the CRE is eliminated as a result of high discharges regulated by USACE for flood protection. This negatively effects the blue crab population dynamics throughout the CRE and makes it difficult to determine cause-and-effect relationships.
29A	8/2/17	Peer Review Panel Written Reviews	Continue benthic infauna monitoring to supplement the *Vallisneria* VEC.	We acknowledge your comments on the benthic infauna monitoring, and that is a good suggestion as an alternative valued ecosystem component (VEC). *Rangia* is one of the most abundant and dominant species here, especially in the upper estuary from S-79 down to Bridge 31.
29B	8/17/17	Dr. Buskey, Peer Review Panel	Do you have *Rangia* spp. here? We've used *Rangia* spp. in Texas as an oligotrophic VEC species. It is in the upper Texas coast, and it is limited to very low salinity. In Texas, we've also looked at the shell growth intervals and related them to salinity. I can you send information on that. It takes a little more effort to monitor for it.	
30	8/2/17	Peer Review Panel Written Reviews	Monitoring - consider cause-and-effect relationship between nutrient loads and eutrophication (dissolved oxygen and Chlorophyll *a*).	We are coordinating with FDEP on the Caloosahatchee TMDL reevaluation process.

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31	8/17/17	Dr. Buskey, Peer Review Panel	In terms of tape grass as a VEC, obviously it gets eaten very fast, and with seagrasses a lot of times it is considered as a habitat as well, and that habitat can go away. What effect does that have on the rest of the ecosystem? It would be nice if you could make that connection a little bit. I know if it's not there, you can't do it, but you mentioned you're doing it in another estuary. It seems like you relied on the VEC part rather than the habitat overlap part that you talked about.	It is true that the droughts of 2001 and 2007 reduced the tape grass habitat in the upper CRE to the point that the proposed habitat utilization study had to be conducted in the upper Loxahatchee River Estuary. While that study targeted the Loxahatchee River Estuary and stands on its own merit, the two estuaries have very different geomorphological histories, watersheds, and recent management practices. Additionally, tape grass can explode in freshwater canals, ponds, lakes, and estuary locations if conditions are conducive, such as the upper Loxahatchee River Estuary after 2005. Thus, it is best to infer the relative habitat value of tape grass from the Loxahatchee River Estuary study but not necessarily use it to quantify potential changes in the CRE with fluctuations in abundance.

PUBLIC VERBAL AND WRITTEN COMMENTS ON DRAFT TECHNICAL DOCUMENT AND MFL REEVALUATION

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32	8/17/17	John Cassani, Calusa Waterkeeper	Regarding your definition of a high salinity event, it seems from a probability context, that 55 consecutive days is overly constraining. If you had one day in that 55-day sequence, that it was perhaps a tidal cycle under 10 psu, then it would throw it out as a high salinity event. It would have been interesting if you would have proposed or demonstrated some probability associated with that concept. The other thing is, depending on who you talk to, there is uncertainty associated with reservoir performance. It would be interesting to understand what your assumptions were regarding reservoir performance in the context of the salinity envelope. It significantly affects the way you characterize the high….whether it's an event you're going to assess in terms of performance.	Plots were rendered to evaluate the distribution of the events that were > 55 days, with the different scenarios, because it is not just a matter of when these events occurred. The distribution also changes. The criteria introduces a fairly rigid definition, when salinity varies around 10 it is not too bad. It is the duration and weighted salinity that does major damage to tape grass. So, the longer the duration, the saltier it gets. If the estuary only drops a couple of parts per thousand for a couple days, that does not affect these plants, but the comment is well taken. A Tape Grass Model was developed and calibrated based on cumulative field, mesocosm, literature, and professional information. It is the only one of its kind in the world at this point. The model was used to evaluate both exposure to salinity ≥ 10, and, recovery when salinity was < 10. The 55-day result was solely based on the definition of significant harm, which requires 2 years for a damaged resource to recover (see Figures 30 and 34 of the Technical Document [SFWMD 2017]). While there is a wide range of possible durations depending upon fractional loss versus gain, the most constraining factor in the duration determination process was the definition of significant harm.
33	8/17/17	John Cassani, Calusa Waterkeeper	I don't think a day or two is ecologically relevant, I would agree with that, but going in and out completely [is relevant].	The 55 days came from two independent analyses; one of the exposure and one of the recovery. When the information is combined and examined, 55 days is the solution for a two-year recovery time.
34	8/17/17	John Cassani, Calusa Waterkeeper	I'm suggesting it would be much higher if you had a broader definition. For example, why did you use the average salinity during those 55 days? If you had said that the average salinity was >10 during those 55 days, I think that would have been more ecologically relevant.	That eliminates the duration element as required for the determination of significant harm.
35	8/17/17	John Cassani, Calusa Waterkeeper	I would hope that the peer review committee did see the 2007 C-43 test cell study. That might give you a better idea of how the reservoir might perform in the context of meeting the MFL. You might not have seen it, I suggest you look at it. If you look at the enabling statute, it says the recovery plan is to be implemented as soon as practicable. Is 16 years practicable? I don't think so.	The C-43 test cell report did not address operation of the reservoir but rather focused on the constructability. The expected performance of the reservoir to meet a restoration target (not MFL) inflow rate was defined as 450 cfs in the PIR.

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36	8/17/17	John Cassani, Calusa Waterkeeper	What concerns me about the modeling, are two potential drivers of rapidly changing landscapes that create more extremes in hydrology. When I go to other CERP meetings they are really struggling with these issues, trying to get their arms around the uncertainty associated with it, more extreme rainfall, and how that plays into the models. That's becoming the elephant in the room. Are there confidence intervals on your estimates? I am not seeing them. Are you taking into account trends and more extreme rainfall events that create this uncertainty? That's perhaps why we're seeing differences in your time steps. The uncertainty lies in the response variables that you can quantify now, all the ecological indicators we have been talking about, extreme events being more important than average conditions, and how you play those factors into your assessment of performance criteria. It comes back to your assumptions of how tape grass responds. You're not doing empirical assessments, you're doing estimates, modeled estimates. It's a little more dynamic than that.	The ability to model salinity, due to the hydrodynamics and what comes into the estuary, we can do with very high confidence, with an r^2 of about 95% on our salinity predictions. Watershed questions related to taking into account potential changes in climate and rain must be deferred to other authorities. As for long-term models accounting for variations in land use and climate, this is a planning-level model, so it is not changing land use historically through time. We had a set condition, and then we ran the 1965 to 2005 climatic period of record through that existing, or future condition. When we calibrated, we use historical changes in land use, but when we ran the simulation model, it is a time stamp with 2012 or 2040 land use. The Tape Grass Model calculates biomass every 45 minutes for 39 years. So, anything that happens over any time scale ranging from an hour to a decade, can be accounted for. That model is calibrated based on mesocosm experiments and field studies for over 16 years. (Dr. Pinckney in response to John Cassani's comment): I will weigh in on this conversation. Nature is very fickle, and predicting nature's responses to unknown variables it is impossible. So, what do we do? We use the best available data we have up to that point. I am fairly satisfied that the District has utilized the available data that they had, and that's what they have to use. They have to have a basis for their opinion. I can understand that Grandfather used to see things here, but science doesn't work that way. We have to have hard data in order to go in those directions. I will throw that out there because I am an ecologist and I'm a modeler too, and people always get confused about why we can't predict the future.
37	8/17/17	John Cassani, Calusa Waterkeeper	You go to your empirical data. There are lots of data. You need to look at a broad range of empirical studies that have been peer reviewed already. I would point you to the 2010 study3 that FGCU did [Tolley et al.] on this system. It looked at different [response] variables, different biota, different species, but they get to some of the concerns that you've addressed.	Do you mean the water column / zooplankton / ichthyoplankton studies? Those were outlined in Component Studies 4 and 5 of the Science Summary (Buzzelli et al. 2017), completed as the precursor to revising the MFL criteria. Component Studies 4 and 5 were directly derived from the Tolley et al. study. The District will continue to consider and evaluate all public comments, data, and suggestions for additional technical analyses, or other information submitted as part of any public workshop. On many occasions, this information is incorporated into technical documents or the rule development process.

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				(Dr. Pinckney in response to John Cassani's comment): I would like to hear from the stakeholders. Is there information out there that isn't included in the District's report? That's what I want to see. If you have a database that wasn't included, then that database needs to be supplied to the district. I don't feel that they are excluding data because they want a certain end point answer to it. If there are missing data, I want to know about it.
38	8/28/17	John Cassani, Calusa Waterkeeper	SFWMD documents use 450 cfs was reported as an appropriate target and ACOE uses 450 as discretionary as part of the Lake Okeechobee regulation schedule.	The Lake Okeechobee Regulation Schedule (LORS2008) does not define the release rate when the schedule is below the Base Flow regulatory release zone. The planning document used as part of the CERP planning process uses 450 cfs as a restoration target for the CRE. The flow recommendation for the MFL is not a restoration target and is designed to prevent significant harm.
39	8/28/17	John Cassani, Calusa Waterkeeper	VEC Recovery failure is a result of failure by SFWMD to implement water shortage restrictions or limit allocations.	Component Study 7 suggests that *Vallisneria* reduction in the CRE was a result of multiple drought events that have occurred in the past. MFLs are not designed to drought-proof the MFL waterbody but rather prevent significant harm.
40	8/28/17	John Cassani, Calusa Waterkeeper	There are several concerns regarding the C-43 Reservoir related to its ability to meet the recommended MFL flow and water quality.	The modeling evaluation provided in Chapter 7 of the draft Technical Document (SFWMD 2017) uses the C-43 Reservoir to evaluate the recommended criteria. Model results show that the recommended flow of 400 cfs is met 97.8% of the months under the future condition scenario. There is also an extensive water quality monitoring plan that must be implemented before surface water from the reservoir is released to the receiving waterbody to ensure state water quality standards are met. For more information regarding the water quality monitoring plan see Annex D, Section D.4 of the PIR (USACE and SFWMD 2010) at the following link: http://141.232.10.32/pm/projects/project_docs/pdp_04_c43/final_pir_nov_2010/110010_vol_3_annx_d_pom_mon_plan.pdf
41	8/28/17	John Cassani, Calusa Waterkeeper	The mesocosm studies used for tape grass to establish a duration for the MFL is an oversimplification of actual conditions. Since 100% of mortality has already occurred, the assumptions about recovery are unsubstantiated considering the ecological change in the system.	The Tape Grass Model was developed and calibrated based on cumulative field, mesocosm, and literature information. It was not derived solely from mesocosm results. It is important to remember that not all the *Vallisneria* shoots were lost resulting from drought conditions in 2001 and 2007. Field

Comment Number	Date	Entity	Comment	Response
				observations, empirical data analyses, and model responses indicate that tape grass could survive if conditions are suitable and it is not over grazed.
42	8/28/17	John Cassani, Calusa Waterkeeper	The Sanibel-Captiva Conservation Foundation clearly demonstrates that a flow as high as 600 cfs at S-79 (without tidal basin flows) during a 30day period is inadequate to meet a salinity of 10 for tape grass (see Figure 1 in letter). Flows > 600.	See Component Study 2 of the Science Summary (Buzzelli et al. 2017), which addresses the flow to achieve a salinity of 10 at the Ft. Myers monitoring station.
43	8/28/17	John Cassani, Calusa Waterkeeper	A study conducted by Tolley et al.3 indicates the flows at S-79 should be much higher than 400 cfs – Tolley et al. study indicated the flows should be 800-1100 cfs to sustain the ecological balance.	The Tolley et al. (2010) study made several estimates of critical inflows for zooplankton ranging from 800 to 1,200 cfs. These estimates were based on relationships between flow and center of abundance, total abundance, and position of the 90^{th} percentile of population distribution. The estimates of critical flow are based largely on visual inspection of graphical plots. We used a statistical approach to avoid the potential of conflicting visual interpretations. The discrepancies between our analysis and the Tolley et al. (2010) study arise from two sources. First, we used predetermined periods over which to average the flow data, rather than picking the lag with the highest correlation coefficient. Averaging periods were limited to those over which flows might be managed. This will affect flow estimates. Secondly, there are some statistical considerations. The impingement analysis will serve as an example. Taking into account the associated error, any one of the statistical estimates for individual taxa overlaps the 1,000 cfs estimated by Tolley et al. (2010) However, the central tendency of results for the seven taxa is about 400 cfs. Our approach along with results and attendant errors were presented in the draft Technical Document (SFWMD 2017) and at the public peer review session.
44	8/17/17	John Cassani, Calusa Waterkeeper	You're looking at 400 cfs, and the lower flow value recommended in the [Tolley et al.] study was 800 cfs.	
45	8/28/17	John Cassani, Calusa Waterkeeper	Calusa Waterkeeper favors tape grass as a representative VEC indicator based on its historic range. Other biota can actively migrate within a salinity range and will be less impacted by extremes, less vulnerable and do not provide the same ecological functions.	This illustrates the difference between a static and a dynamic VEC.
46	8/29/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	Significant and serious harm are supposed to trigger Phase III and IV water shortage cutbacks. The MFL exempted the SFWMD from implementing any phased water restrictions until the recovery strategy is available.	There are multiple factors considered for determining the severity of a drought and various phases of water restrictions (See Chapter 40E-20, Florida Administrative Code [F.A.C.]). The MFL rule does not exempt water shortage restrictions from being declared or implemented by the District Governing Board.

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47	8/29/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	Without a recovery strategy in place the estuary is at the mercy of the SFWMD with no alternative for recovery which creates a shifting baseline and serious harm has occurred.	The *2005-2006* and *2012 Lower West Coast Water Supply Plan Updates* (SFWMD 2006, 2012) make it clear that the existing MFL of 300 cfs does not provide sufficient flows to prevent significant harm and that additional storage is needed within the watershed to meet the MFL criteria. Exceedances and Violations of the criteria are expected to occur until the recovery plan is in place. The purpose of this recovery strategy is to meet the MFL criteria to prevent significant harm, not restore the estuary to some prealtered condition.
48	8/29/17 8/17/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	Although the MFL was established in 2001, it has not prevented a permanent and irreversible loss of over 1,000 acres of tape grass habitat. (Rae Ann Wessel, Sanibel-Captiva Conservation Foundation): In 1993, tape grass extended down river to Whiskey Creek. By 2003, we had lost the grass up to just west of the U.S. 41 bridges. By 2010, we were just between the bridges. By 2011, we were on the east side of the bridges. I offer this because we have lost, as others have said, over a 1,000 acres of freshwater tape grass. In 2006, the district said we will never recover that 1,000 acres downstream. That is, by definition, serious harm. Something is supposed to happen to prevent serious harm when you have something that is forever lost. This is part of the concern, because when we're talking about a shifting baseline, we just set a new benchmark at each stage, and then we're working on a reduced habitat capacity and productivity capacity. We are already experiencing serious harm and really nothing is changing that dynamic, it is getting worse.	Previous density and distribution of tape grass has been predicated on the study conducted by Hoffacker in 1993, a year that in Hoffacker's opinion exhibited unusually lush and wide spread growth of SAV, including tape grass. There may be 1,000 fewer acres of tape grass today then there were in 1993, but 1993 was atypical. Most of the tape grass losses had already occurred before the MFL was established in 2001.
49	8/29/17 8/17/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	District staff should provide a parallel analysis using existing, real time, monitored flow and salinity data on shorter time scales to reflect the variability and responses of the natural system to varying conditions. During the 2016-17 dry season, it took 730 cfs to return rising salinity to the MFL target. Longer periods of record mask current conditions affected by increases in impervious surface, consumptive uses, and losses in groundwater recovery and sea level rise. (Rae Ann Wessel, Sanibel-Captiva Conservation Foundation): We need to use as much actual data [as possible], we need to carve it into those time periods where you have known conditions. We have to evaluate this on a living timescale. So often in these meetings we are using a 40-year period of record, and it is getting rectified for this or that. It only takes 30	The empirical analysis performed as part of this reevaluation used long-term actual data. It is well understood there is going to be significant uncertainty in establishing a specific flow target for a specific salinity at a specific location as demonstrated in our statistical analysis. We agree that more uncertainty analysis might be needed. The final peer review report did not identify uncertainty as an area of concern. As for sea level rise, we have tested a quite wide range of sea level rise, from 2.5 to 10 millimeters per year and simulated its potential impact on salinity. But it is well understood there is tremendous uncertainty in sea level rise itself. The modeling results show that there will be an insignificant change in sea level rise over the next 20 years.

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			days to kill tape grass or to kill oysters. We need to pin down the science that we do know, using actual data, and using living timescales, and understanding a shifting baseline is being introduced. Let's look at 6 months of actual data, a wet season or a dry season, or some other condition. A 30-day moving average increasing, for determination of an MFL, to over 50 days, that is dead. I don't really see the justification in it. (Rae Ann Wessel, Sanibel-Captiva Conservation Foundation): We have issues with sea level rise. That tidal force is coming up the river, needing more water to offset it, if we're going to manage a low salinity zone and have a productive estuary. I'd like to see actual data used and graphed in specific periods, both for high flow and low flow, but you're really focused on low flow for the MFL.	
50	8/29/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	Verify that the exponent used in Figure A14s is correct. Suggest using steady flow periods as depicted in Figure 3 (in letter). We also suggest using a trend analysis.	The exponent in Figure A-14S of Component Study 2 of the Science Summary (Buzzelli et al. 2017) was confirmed to be correct.
51	8/29/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	A study conducted by Tolley et al. 20103 indicate the flows at S-79 should be 800-1,000 cfs to avoid habitat compression and loss of phyto- and zooplankton. Based on the compiled regressions of organism center of abundance vs. freshwater inflow, a number of species would be relocated downstream of this restricted portion of the tidal river at inflows of 800-1,000 cfs.	See the responses to Comments 43 and 44.
52	8/29/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	There is no justification for moving away from the existing 10 psu 30-day moving average "harm" salinity criteria. We are also requesting scientific literature and justification to support the 55 consecutive day threshold and for dropping the 20 psu 1-day harm threshold.	All of the justification and supporting science information for changing the MFL criteria were conveyed during the two-day Science Symposium, held in September 2016, and in the Science Summary (Buzzelli et al. 2017) as well as in the draft Technical Document (SFWMD 2017). MFL compliance data show that the a salinity of 20 1-day criterion was never exceeded before the salinity of 10 30-day moving average criterion was exceeded.
53	8/29/17 8/17/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	We suggest adding a low-salinity zone as a physical spatial target downstream of S-79 with a goal of maintaining a continuous salinity gradient, when possible, to provide productive habitat for fish and wildlife species. This physical spatial indicator could be used to complement other indicators. (James Evans, City of Sanibel):Regarding indicators, have you considered looking at a spatial low salinity zone target based on habitat	The concept of the "low salinity zone or LSZ" was adopted from a conceptual model of large temperate estuaries such as Chesapeake Bay. It is derived from a generalized sequence of down-estuary abiotic gradients. However, these gradients can be inconsistent or absent in subtropical estuaries with modified watersheds and managed inflow. In fact, our studies demonstrated that salinity in the CRE is often constant from 0 to 12 km downstream of S-79

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			volume? I know you looked at it in regard to ichthyoplankton and zooplankton. However, have you looked at how you can maintain a continuous low salinity gradient downstream of S-79, to maintain that 0.5 to 6.0 psu low salinity zone which is obviously very important for a lot of estuarine indicator species? Obviously the changes in geomorphology of the river, and that constriction, and the changes in flow can affect the habitat volume considerably, especially upstream of Beautiful Island.	(see Figure A-18 of the Science Summary [Buzzelli et al. 2017]). This attribute along with the absence of lateral shoals or fringing wetlands makes the LSZ difficult to define in the CRE.
54	8/29/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	We encourage the use of local rainfall data to establish seasonal, ecological targets for the estuary. Dry season studies could be flawed if using Nov.-Apr. to define the dry season.	The District defines the wet season as May through October and the dry season as November through April. See Component Study 10 of the Science Summary (Buzzelli et al. 2017) which links local dry season rainfall to blue crab harvest data.
55	8/29/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	The modeled and measured data for phytoplankton and tape grass were not given the same weight. A heavier weighting should be assigned to measured data which brings into the question the margin of safety incorporated into the MFL.	Each indicator was treated equally in our assessment of magnitude.
56	8/29/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	The error and uncertainty of the *Vallisneria* model is not reported nor are the uncertainty of the predictions.	See Component Study 8 of the Science Summary (Buzzelli et al. 2017).
57	8/29/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	A plan should be included with this MFL to implement water shortage cutbacks to all users, not just natural systems.	Chapter 40E-21, F.A.C. (Water Shortage Plan) sets out criteria for declaring and implementing a water shortage and provides four different phases of cutbacks for existing users (from 15 to 60%) depending on the drought severity. A water shortage declaration for Phases 1 through 4 are determined by monitoring the natural system response to the drought conditions. Also please see the responses to Comments 39 and 46 above.
58	8/29/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	Technical Document, Chapter 1: Introduction: Line 1600-1602 (now 1465-1467): If the SFWMD Governing Board has authority to not consider historical conditions if the water body has been significantly altered, then the SFWMD cannot expect a “natural systems failure” to occur during droughts as the system cannot be expected to retain a historical flow based on ‘natural’ groundwater or surface water inputs.	The comment is acknowledged.
59	8/29/17	City of Sanibel and Sanibel-Captiva	Technical Document, Chapter 1: Introduction:	The flow of 150–200 cfs was the estimate in the 2003 MFL update (SFWMD2003), which was based on linear reservoir model results. For this

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		Conservation Foundation	Line 1722 (now 1586) and 1727 (now 1591): What is the probability of Tidal basin flows of 150-200 cfs? What amount of rainfall is required to sustain 150-200 cfs?	reevaluation, the Watershed Model (WaSh model) was used to simulate tidal basin inflow. The time series of simulated daily inflow based on 2012 land use data shows that about 68% of days (from 1968 to 2012) are with flow greater than 150 cfs. It is almost impossible to determine a single number for rainfall sustaining this daily flow because too many environmental factors are involved in runoff generation from rainfall.
60	8/29/17 8/17/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	Technical Document, Chapter 2: Line 1991 (now 1855): Based on actual rainfall data from Lee County, why did the District not consider May and October as part of the dry season? (James Evans, City of Sanibel): My question is related to the wet season/dry season definitions that you have. You have the wet season defined as May through October and the dry season as November through April. Based on the data that I looked at, at Page Field in particular, it looks like the historical dry season in the Caloosahatchee would include May and October timeframes as well. When you look at the mean rainfall from 1994 to present, it looks like May was only 3.27", and this is Lee County data, and mean rainfall in October was 3.2", but June through September the average was above 9.5". So, it's much closer to dry season rainfall data than wet season rainfall data. That might be something that is influencing the model. I don't know if you're using continuous rainfall data in the model and maybe it doesn't matter how you separate out the wet season and dry season. (Rae Ann Wessel, Sanibel-Captiva Conservation Foundation): The local wet season is important, here we have very specific wet seasons and dry seasons. We are almost always in an MFL in May and by the second week in October. Those are known monitoring and measured conditions. We do a weekly report that documents this.	See the response to Comment 54. Continuous rainfall data are used in the watershed hydrological model. This separation of wet and dry seasons does not impact model results. We have used a standard definition for wet and dry seasons that is used for reporting under the Northern Everglades and Estuaries Protection Program in the South Florida Environmental Reports. The analyses presented in the document were intended to understand the responses of a series of estuarine indicators to low fresh water inflows during the dry season. There is no seasonality built into the model. It is all post-processing, assuming the dry season is defined by those months.
61	8/29/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	Technical Document, Chapter 3 Line 2317 (now 2182): The WaSh model should report error and uncertainty with the predictions. Why is SFWMD recommending a lower flow for the MFL than other independent research studies (e.g., CERP RECOVER, HydroPlan LLC)?	The WaSh model was used to simulate the surface water and groundwater inflow from the tidal basin. The long-term simulation inflow time series was provided to the estuary hydrodynamic/salinity model as input. The salinity model output was used in the ecological model as input. The suite of models was not used to determine the amount of minimum flow but to verify scenarios. The uncertainty information of the WaSh model does not help in determining MFL through this modeling line. On the other hand, to determine the uncertainty of the WaSh model, we need to determine

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				uncertainties existing in input data, such as rainfall, evapotranspiration (ET), land use, aquifer, boundary conditions, and uncertainties in model parameters (e.g., ET coefficient for various land use types, infiltration parameters for various soil types, aquifer conductivities, canal roughness). Almost all of these uncertainties can not be precisely quantified. The flow for the MFL is based on the component studies (as described in the Science Summary [Buzzelli et al. 2017]) and other analyses and modeling completed by the District, not on other studies that are geared more toward restoration of this waterbody.
62	8/29/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	Technical Document, Chapter 4: Figure 15 states map is from 2001 but cites Hoffacker 1994 and much of the tape grass was wiped out by 1998. Given the resources committed by the Governing Board an accurate spatial map of the SAV coverage within the CRE within the past 5 years should be provided.	SAV is mapped by the CERP Restoration Coordination and Verification (RECOVER). Figure 15 has been deleted and replaced. The new figure has been added to Chapter 4, which shows the spatial extent of SAV (seagrass) in the CRE (Figure 20 in final report).
63	8/29/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	Technical Document, Chapter 5: Lines 2672 (now 2539) and 2996 (now 2864): The multiple indicator approach should be weighed for the final analysis.	Comment acknowledged.
64	8/29/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	Technical Document, Chapter 5: Line 3291 (now 3158): The hyperbolic function curve was derived from model outcomes and not from experimental data. While the simulation model for recovery is the basis for the recovery curve; the uncertainty of the model prediction or an error term for recovery is not included. Also, the model calibration data were not included to see how the tape grass growth model performed.	Model uncertainty is addressed in Component Study 8 of the Science Summary (Buzzelli et al. 2017). The model responds to salinity changes in a logical and consistent way. We are confident in using it as a forecasting tool.
65	8/29/17	City of Sanibel and Sanibel-Captiva Conservation Foundation	Technical Document, Chapter 5: Line 3364 (now 3232): It would be nice to include duration terms from other component studies to corroborate. Actual recovery of tape grass has not occurred in the CRE since the major droughts in 2001 and 2007 which indicates the tape grass model is optimistic.	As discussed during the Public Peer Review Session on August 17, 2017, all of the indicators were used to evaluate magnitude but for only a couple of indicators did we have sufficient data/information to determine duration and/or return frequencies.
66	8/17/17	Sanibel-Captiva Conservation Foundation	(Rae Ann Wessel, Sanibel-Captiva Conservation Foundation): As for tidal basin inflows, we have two major freshwater tidal basin inflows, Telegraph Creek up near S-79, and Orange River near I-75. When it is dry, or we are in drought, we do not get the modeled 150-200 cfs inflows, the salinity just continues to increase. We have seen that, between 2007 and 2012, when we were in a year-on-year drought, at the lock [S-79], at that estuary interface,	We believe that 150–200 cfs is the average flow for the long-term. For extremely dry years, such as 2001 and 2007, the flow for months of the dry season from the Tidal Basin are much lower than this value. Based on the modeled results, monthly average flow for April and May 2007 were 58 and 25 cfs, respectively, and monthly flow for April 2001 was -9.6 cfs.

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			where it should be no more than 5 psu, it was over 20 psu each year. That has destroyed tape grass, compressed all the phytoplankton and zooplankton, the whole productivity of the system is basically lost. Then you're losing water quality, you're losing sediment stabilization, you're losing oxygen, you're getting hypoxia, it is a cascading situation. In 2007 to 2011, we had a year-on-year drought where we did not meet any of those MFLs. The Caloosahatchee Estuary needs about 1" of water from Lake Okeechobee during a drought or dry season, to get even close to a 10 psu at the Fort Myers bridges. We got 1" over 8 months, and you don't get recovery by getting the water right the next year, it takes years.	MFLs are not designed to drought-proof the MFL waterbody but rather prevent significant harm. When the MFL was established in 2001, it was acknowledged in the water supply planning documents (SFWMD 2006, 2012) that MFL exceedances and violations would occur until the recovery strategy was constructed and operational.
67	8/17/17	Sanibel-Captiva Conservation Foundation	(Rick Bartleson, Sanibel-Captiva Conservation Foundation): About the loss of groundwater from reduction in recharge of the aquifer from development, that's definitely happening. Over 50% of Lee County was wetlands, and now it is less than 18% and it is probably decreasing about a percent per year. One of the graphs in the district's report shows the amount of flow needed from S-79 to provide 10 ppt at Fort Myers yacht basin. Their data pretty much has a straight line across it for a trend line of 400 cfs. However, if you add in recent year data, we really need over 600 cfs in recent years, every year, and that's a trend, not a straight line, because we have less recharge area. Going along with that, if you have a cfs of 400 at S-79 for the MFL, that's going to give you 10 ppt at Beautiful Island, 15 ppt at Fort Myers yacht basin, which where the old MFL was 10 ppt. In that case, you lose tape grass habitat from Beautiful Island to Fort Myers where all of the tape grass exists and most of it has existed in recent years. So, it is sort of saying, we don't need tape grass anymore, never mind the valued ecosystem component.	The groundwater contribution is given in the WaSh model report (Appendix D, Table D-8 of draft Technical Document [SFWMD 2017]). 2008/2009 land use data were used for the WaSh model calibration. In that land use data, the wetland percentage is about 15%. The model did not include the case of land use, which has 50% wetland, therefore the model results cannot address the groundwater reduction. In Component Study 2 of the Science Summary (Buzzelli et al. 2017), we analyzed 20 years of salinity and inflow data. For each water year, we calculated 12 monthly salinities at the Ft. Myers monitoring station and 12 monthly average inflows. Then we derived a series of regressions. We did an exponential regression for each of those years, and for every year, we rearranged that equation and calculated the amount of inflow it took to get a salinity of 10 at Ft. Myers. The end result of those analyses, over 20 years, is the amount of water from S-79 required to reach a salinity of 10 at Fort Myers varies, from 70 cfs to over 700 cfs. It varies all the time. The reason it varies is because of circulation and salinity characteristics in the CRE.
68	8/17/17	Conservancy of Southwest Florida	(Marisa Carrozzo, Conservancy of Southwest Florida): My question relates to the original MFL modeling assumptions, roughly estimating that 150-200 cfs from the tidal basin was needed in order to meet the MFL. Does this model update make a similar assumption that the inflows from the tidal basin would be supplemented with the 400 cfs at S-79?	The 400 cfs recommended as part of the revised MFL criteria only includes discharges from S-79. It does not include the contributions from the Tidal Basin.

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69	8/17/17	Conservancy of Southwest Florida	(Marisa Carrozzo, Conservancy of Southwest Florida): The recovery strategy for the MFL is reliant on the C-43 reservoir and the water reservation. If we get to the point where the reservoir is operational but without water quality treatment, will we be in a position of either sacrificing water flow to the estuary or water quality?	Design and construction of the C-43 Reservoir did not incorporate a water quality treatment component. However, an extensive monitoring protocol is required as part of the PIR for the project (USACE and SFWMD 2010) before any water is released from the C-43 Reservoir to ensure that state water quality standards are met.
70	9/1/17	Conservancy of Southwest Florida	The Conservancy is concerned that the proposed MFL does not meet the necessary threshold of preventing significant harm, or in this instance, further significant harm, to the resource. The Conservancy does not support the proposed MFL criteria for the reasons outlined [in submitted comments].	The revised recommended MFL criteria are based on the best available science to prevent significant harm and to provide protection of the ecological indicators within the CRE.
71	9/1/17	Conservancy of Southwest Florida	The Caloosahatchee has sufficient real-time monitoring data and studies on which to base an MFL re-evaluation that takes into account the most sensitive taxa and ecological indicators.	The MFL criteria are based on the best available science using a resource-based approach from multiple ecological indicators in the CRE.
72	9/1/17	Conservancy of Southwest Florida	An appropriate flow target should account for antecedent or existing conditions, as well as monitoring real world results of flows on salinity levels.	The flow target recommended for the revised CRE MFL criteria is based on the 11 component studies that were completed as part of the Science Summary (Buzzelli et al. 2017) and additional technical analyses that were completed to determine the magnitude, duration, and return frequency components for the MFL.
73	9/1/17 8/17/17	Conservancy of Southwest Florida	Multiple studies and real-time monitoring data indicate, to support a salinity of 10 psu at the Fort Myers station and protect ecological indicators such as *Vallisneria* and zooplankton, flows much greater than 400 cfs at S-79 are required. The Conservancy has attached a compendium4 which outlines many of the studies that support flows greater than 400 cfs. Tolley, et al.3 point to 800-1200 cfs to avoid habitat compression against S-79 and loss of species due to increased predation, etc. The Sanibel-Captiva Conservation Foundation and City of Sanibel provided information [following August 17, 2017 peer review session] which shows, between December 2016 and May 2017, flows in the range of 730 cfs are required to achieve the 10 psu target at Fort Myers. (Rae Ann Wessel, Sanibel-Captiva Conservation Foundation): You [Peer Review Panel] asked the district to use actual data to look at targeted timeframes. We did this at the Marine Lab from December 2016 through May [2017], and we had a variety of conditions. When we get lower flows, we have higher salinity, and we're in the MFL exceedance…it takes about 730 cfs to get us back to meeting	See the responses to Comments 43, 44 and 49.

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			the MFL. That's nowhere close to 400 cfs. We're exceeding 400, 300 [cfs] over and over again.	
74	9/1/17	Conservancy of Southwest Florida	The range of flow for the various indicators did not appear to include a margin of safety by simply taking the median value of 400 cfs as the MFL magnitude.	The magnitude of flows from the 11 component studies described in the Science Summary Buzzelli et al. 2017), revealed the following flows at S-79: 367 cfs (Geometric Mean), 380 (Arithmetic Mean), and 400 cfs (Median). From a scientific standpoint, these indicators do not recognize these minor differences in flows. The higher flow target of 400 cfs was chosen to prevent significant harm to the crab fishery and to prevent impingement of zooplankton at S-79.
75	9/1/17	Conservancy of Southwest Florida	55 consecutive days above [a salinity of] 10 results in a loss of 75% of the resource (*Vallisneria* – tape grass), a harm that is far greater than significant. Instead of basing the duration on a two-year recovery model, the MFL duration should be based on preventing significant and serious harm. Recovery is contingent on suitable conditions, salinity, flow, light availability, etc. that may or may not actually occur within a two-year timeframe after a 75% loss.	See the responses to Comments 32, 34, 41 and 64.
76	9/1/17 8/17/17	Conservancy of Southwest Florida	Exceedances of the current MFL occur on a yearly basis, and recovery of tape grass has not been achieved in the two years which form the basis for the recovery assumption. There is no reason to expect that to change in the near future, since the Caloosahatchee's recovery strategy relies on the C-43 Reservoir which will not be operational until 2022. (Rae Ann Wessel, Sanibel-Captiva Conservation Foundation): The prevention/recovery plan is the C-43 reservoir. It hasn't been available for 16 years. So, we have gone forward with a management scheme that says "well, we can't initiate water cut-backs for other users because your prevention/recovery strategy doesn't exist". That wasn't the intent of creating the prevention/recovery strategy. We still won't have that prevention/recovery strategy for another 5 years, if we stay on track, and at that, it is about a 30% solution, if it works. In 2007 the test cells that were created, actually grew algae. While in 2007, we did have that water, but because it was of such poor quality, we didn't use it.	It is important to understand that the majority of the tape grass population was lost before establishment of the MFL in 2001. Tape grass has not recovered, in part, because of severe drought conditions that occurred in 2001, 2007–2008 and 2011. The MFL recovery strategy is designed to provide conditions under which tape grass could be sustained if the population was recovered in the future. Again, the MFL is not designed to address recovery of a specific species, address all of the water storage issues within the watershed, or drought-proof the waterbody.
77	9/1/17	Conservancy of Southwest Florida	The proposed MFL does not adequately take into account salinity variability and extreme swings from too little to too much freshwater flow and vice versa . For example, in June 2017, the Caloosahatchee went from a two-month MFL exceedance to nearly twice the high flow	The MFL is not designed to address extreme (high) discharges to the estuary due to lack of available storage within the watershed.

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			range of 2,800 cfs within one week1. Peer review panelists raised questions in their written comments regarding salinity variability, averaging and extremes (Jennifer Beseres Pollack, Page 5 and James Pinckney, Page 3). [1]Caloosahatchee & Estuary Condition Report, June 6-12, 2017. Available at http://sccf.org/.	See the responses to Comments 12 and 67. Also, please see Component Study 2 in the Science Summary (Buzzelli et al. 2017).
78	9/1/17	Conservancy of Southwest Florida	The proposed MFL has removed the single day excursion in the current MFL rule that trigger an MFL exceedance with a one-day spike in salinity over 20 psu. Thus, the proposed MFL does not have a similar mechanism to identify harm situations that result in a quick and extreme change in salinity.	See the response to Comment 52.
79	9/1/17	Conservancy of Southwest Florida	The C-43 Reservoir is not scheduled for completion until 2022, and in the interim since 2001, no baseline or statutory reservation was adopted in order to protect the river from harm caused by the reoccurring low flow periods. As part of the MFL re-evaluation, the Conservancy urges the SFWMD to also adopt a water reservation that will protect the ecology of the river from additional loss of resources.	The District does not have any plans to establish another water reservation rule before completion of the C-43 Reservoir. However, the current water reservation rule in 40E-10.041 (3), F.A.C., does contain language that allows for the revisions of this water reservation rule once it becomes operational.
80	8/17/17	Florida Farm Bureau Federation	(Gary Ritter, Florida Farm Bureau Federation): This is a large, complex watershed. I look at it as 1/6 (one sixth) of the entire watershed, if you include the Kissimmee, St. Lucie, Caloosahatchee, Lake Okeechobee, the Everglades, and modified waters Homestead area. I was pleased to hear that you all are collaborating at least with FDEP because they are running a parallel course with modeling in the Caloosahatchee. There is an ongoing effort with the Lake Okeechobee Watershed Project where Aquifer Storage and Recovery (ASR) wells are being discussed, putting excess water back in the system when the system needs it. I am assuming that there is collaboration there, so that in the future, some of that water is earmarked for the Caloosahatchee. There are large storage areas in that particular basin as well. Another project that is going on right now involves Nicodemus Slough and Lake Hicpochee. How do all of these projects relate to, and help, what you are trying to do with the MFLs? Those projects should be taken into consideration. In the project area you define, is the Western Everglades Restoration Project including another modeling effort?	When CERP components become operational, the System Operating Manual will have all of those components work with each other. However, right now those projects are just being finalized and documented. As each CERP project comes online, it will have its own operating and system manual. One project that will have an effect on Lake Okeechobee levels is the Central Everglades Planning Project (CEPP), which will send more water south. This project is going to lower the lake stage and make less water available for the Caloosahatchee. CEPP was included in the future simulations. No other CERP projects were included in the simulation. Nicodemus Slough Basin was removed from the Agricultural Field Scale Irrigation Requirements Simulation/Water Balance (AFSIRS/WATBAL) future simulation since it will be hydrologically disconnected from the Caloosahatchee Watershed in the future. In September 2017, the CERP Lake Okeechobee Watershed Project Delivery Team will be giving the District a series of inflows, and we will run the hydrodynamic model with those data to provide salinity time series. Oyster simulations for the St. Lucie and the Caloosahatchee River estuaries will be performed as the first cut to determine the effectiveness of the project.

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				The Western Everglades Restoration Project (WERP) modeling is tailored to answer the questions that arise for that area. See the following link for more information: www.saj.usace.army.mil/Missions/Environmental/Ecosystem-Restoration/Western-Everglades-Restoration-Project/
81	8/17/17	Florida Gulf Coast University	(James Douglass, Florida Gulf Coast University): Two of the scientific results today were the past salinity and tape grass model, where you extrapolated what the salinity and tape grasses were like in the past, and also the model that incorporated various centimeters of sea level rise and how much of an increase in salinity that would mean. Those are both really interesting things, especially in combination with some of the issues that have been brought up here today with concerns about the loss of natural storage capacity in the watershed, which is an ongoing process. When you were looking into the past, and saying this is what the salinity was like in the past, did you take into account how much natural storage capacity and flow regulation might have changed from 1967 to 2017? Was the salinity really 30 psu frequently in the estuary? Do we have any data to check that? Do we know how much we have lost the groundwater flow and things like that? These are really important questions that we need to take into account in the MFL development.	Changing storage capacity and flow regulation are built into our modeled flow scenarios. The MFL criteria were evaluated and based on the existing condition of the estuary and the current alterations that previously occurred in the past would remain in the future. The existing alterations that have occurred in the past will be taken into account by the Governing Board when determining an MFL for the CRE.
82	8/17/17	Johnson Engineering	(David Ceilley, Johnson Engineering): For a recovery MFL, we need to look beyond just the salinity. Right now, herbivory pressure is so extreme that, as the District mentioned, we have to cage the material that we plant to prevent it from being grazed. Why is that important? Well, the plants are dioecious, they are not seeding, they are not producing seed pods. The data from Dr. Douglass's work and the District's work show that, for years, we have had a flat line in a lot of areas where *Vallisneria* used to be very, very abundant. As far as the long term tape grass model, it seems to implicate that there wasn't much *Vallisneria* in the estuary back in the 60's, 70's, and 80's. That is a mischaracterization of probably what was there. We don't have any mapping data other than the 1993 map that was done for the District. There has been an awful lot of land use change in this area. I saw that the data set looked at 1967 to 2006. What about 2006 to 2017? We've seen a complete collapse in the system, except the vegetative growth we've seen in the last couple of years with relatively decent rainfall.	We know the inflow through S-79 since 1966. We can predict salinity with 95% confidence. We know the salinity tolerances of *Vallisneria*. When we put this altogether, the Tape Grass Model simply tracks changes in tape grass over time. The model accurately depicts the observed changes in tape grass since the mid-1990s. See Component Study 8 in the Science Summary (Buzzelli et al. 2017), which addresses herbivory.

Comment Number	Date	Entity	Comment	Response
			Without calibration of models with real data, then you're just speculating.	
83	8/17/17	Johnson Engineering	(David Ceilley, Johnson Engineering):The long-term tape grass model seems to indicate that we had very wet years. We did have a wet year in 1995. The mapping of over 2,000 acres of *Vallisneria*, done in 1993, preceded that 1995 heavy rain event, and followed several dry years. In 1993, Allen Hoffacker said that there were no releases, no releases from S-79 because they were working on renovating the locks. My point is, the watershed provided a lot of that fresh water. Over 28 years, there have been rapid land use changes, a dramatic increase, and a three-fold increase in population. You could project back in time to say that most of the fresh water came from the watershed, a lot of it. We've seen consumptive use permits, we've seen groundwater drawdown, these data are available. USGS has looked at this. In 1973, if you put a well in Page Field, water would squirt out of the ground. It was Artesian. Harry Gottlieb with USGS has documented this. We have a cone of depression in this area. Consumptive use permits for single-family wells continue to be permitted. A shallow well of 40 feet at a house I bought was dry. At 140 feet, we do have fresh water. All these things need to be considered in your modeling and it doesn't seem like some of it was. I suspect that the projections back in time to the 60's and 70's to say that *Vallisneria* was not there are just erroneous and not based on the reality that we've seen.	See the response to Comment 82. The regional modeling that was completed does not include the aquifer system for the CRE area. It is a surface water accounting model. The models were used to provide flows from Lake Okeechobee and runoff from the basins between Lake Okeechobee and the S-79 structure. Changes in demands that would affect the amount of runoff entering the C-43 Canal and changes that would affect the volume of Lake Okeechobee water were modeled with the best available tools. Water supply planning efforts cover the effects of consumptive use permitting on available water. The modeling approach not only considered the existing conditions (existing demands) but also evaluated future conditions with demands projected out to 2040.
84	8/17/17	Johnson Engineering	(David Ceilley, Johnson Engineering): Why aren't we integrating the TMDLs for the Caloosahatchee River with the discharges from the reservoir? There are Stormwater Treatment Areas (STA) that could be built as part of that reservoir, but they're not on the books right now. Why not? I think the depth on the slide was a 15-25' reservoir. With the light attenuation coefficients that we've seen, and CDOM as high as it is, nothing is going to grow in that reservoir, possibly Hydrilla in some areas. It will be a cesspool for Cyanobacteria and we're going to have a real problem meeting those discharge TMDLs to the river without STAs. I think it's time that we got some focus on water treatment as well as stormwater storage.	See the responses to Comments 6A1 and 69. This MFL reevaluation was done for a completely different purpose, which focuses on dry season inflows. This STA comment is outside of the scope of the MFL reevaluation process. STAs were not part of the original PIR (USACE and SFWMD 2010) design or part of congressional authorization or appropriation process.
85	8/17/17	Lee County	(Sam Lee, Lee County): I think there were 4 or 5 different models, and each model has its own	In our application of the models, the output of one model was used as boundary condition or

Comment Number	Date	Entity	Comment	Response
			uncertainties. When you combine them, and their uncertainties, they could be cancelled out, but it could create much more uncertainty if you do not consider the overall impact of them all.	input for the other model. For example, outputs of flow at S-79 and the Tidal Basin from the hydrological models were used as boundary conditions for the hydrodynamic model and the salinity output from the hydrodynamic model was used as input for the Tape Grass Model. There are errors for each model. However, each of them was calibrated independently, so the uncertainty is still well described by the error statistics reported for each model. The modeling was not used to derive the MFL but to look at the range of climatic conditions experienced in the period of record and see if it can be met by the system.
86	9/1/17	Lee County	The method used to derive the 400 cfs proposed MFL using the concept of dynamic habitat overlap will by default not provide enough water to prevent an exceedance of the salinity at Fort Myers. Using an average or median from several models and measured data, with no regard for error, will provide inadequate flows 50% of the time. Measured flow data verses salinity at Fort Myers has shown that the current 450 and 650 cfs is not enough during common hydrological conditions. At a minimum, the error should be built into the proposed MFL to allow for differing hydrologic conditions.	Please see Component Study 2 of the Science Summary (Buzzelli et al. 2017; now Figures A-13 through A-15, Table A-7 in this final report) The amount of freshwater inflow associated with a salinity of 10 at the Ft. Myers monitoring station varies from 70 to 773 cfs with an average + standard deviation (SD) of 446 + 218 cfs. A single estimate of 486 cfs resulted when all the monthly values from all water years were combined (Figure A-13B in this final report). Component Study 2 provided only one of the indicator estimates used to calculate the magnitude component of the proposed MFL rule. Figure A-29, Table A-10, of this final report and the supporting text explain the approach to combining the indicator estimates. The averages and standard deviations of the magnitude of the minimum inflow rate (cfs) from 8 different indicators were combined. A simple arithmetic approach provided a grand mean + SD of 381 + 104 cfs. The median value of the combined indicators was 400 cfs with a range of 283–457 for one SD. Finally, a value of 365 cfs resulted from combining the indicators through the normal probability density function. Thus, the effects of different indicators, research methods, periods of records, and statistical uncertainty were included in the final calculation of magnitude.
87	9/1/17	Lee County	Measured data should be used as opposed to modeled data when available. We see no justification in averaging modeled data with real data for the same parameter. For example, Val Data and Val Model are both present, and used in the calculated proposed MFL. Why use the modeled data for the MFL when we have better measured data available for the calculation?	See Component Studies 7 and 8 of the Science Summary (Buzzelli et al. 2017).
88	9/1/17	Lee County	We can find no scientific reason to use 55 consecutive days for salinity concentrations, opposed to the 30-day average of the current	See the responses to Comments 34, 41, and 64.

Comment Number	Date	Entity	Comment	Response
			MFL, which does have a scientific basis. Please provide the backup for this assumption.	
89	9/1/17	Lee County	There was discussion at the peer review session on the value of incorporating water quality modeling when evaluating the flow needed to maintain a healthy ecosystem. Concurrent with this process, the Florida Department of Environmental Protection (FDEP) is updating the TMDL/BMAP model. We urge SFWMD staff to collaborate with FDEP, who has developed a calibrated model of the Caloosahatchee River Estuary for TMDL purposes.	The CH3D model was used for evaluating the salinity conditions within the CRE as part of the MFL reevaluation. The District is coordinating with FDEP on the TMDL as it relates to flows to the estuary. It is important to understand that these two initiatives are being implemented for two completely different purposes.
90	8/17/17	Member of Audience	(Member of Audience): I noticed that in the zooplankton study Cassondra Thomas mentioned, a 500 µm mesh sieve was used. You can't catch *Acartia*, for example, with that.	Yes, you recommended a 153-micrometer (µm) mesh, and I think Robert Chamberlain (Chamerlain et al. 2003) used both 500- and 240-µm mesh. But the Tolley et al. (2010) study used the 500-µm mesh. *Acartia* sp. was actually the dominant species of zooplankton captured in the Chamberlain et al. (2003) study accounting for approximately 50% of total abundance. The Tolley et al. (2010) study also successfully captured *Acartia* sp., up to 9,000 per liter on some sampling events.
91	8/17/17	Member of Audience	(Member of Audience): I am glad we're doing this exercise. I've been involved in the process for over 16 years and there have been many occasions when the Caloosahatchee River has not even been able to receive the 300 cubic feet per second (flow) which is the minimum flow level currently. I am curious why you're going to establish a new reasonable level for the estuary when you can't even provide to the estuary currently the water that is called for by law.	There has been a lot of concern here on the west coast about the health of the estuary. The District Governing Board provided direction to move forward with additional research and funding to make sure the best available information was used to reevaluate the MFL. That is the purpose of this reevaluation process. The C-43 Reservoir is the recovery strategy needed to meet the recommended minimum flow of 400 cfs at the S-79 structure.
92	8/17/17	Member of Audience	(Member of Audience): Your last slide about the reservoir, are we going to hear more about the design configuration and the treatment of water rather than just volumes at some point?	No, the purpose of the public peer review session is to focus on how we arrived at the revised MFL criteria and to communicate with the peer review panel to make sure we understand their technical guidance to the District. Additional information on the reservoir will be available during the rule development process.
93	8/17/17	Member of Audience	(Member of Audience): I think it is important to recognize the fact that the C-44 reservoir has two Stormwater Treatment Area (STA) components, in other words, filter marshes, and the C-43 reservoir currently does not have any treatment. It's just a big bathtub. As an aquatic ecologist, I am concerned about cyanobacteria blooms. I think it is important as we're modeling this, that we consider the biology and the nutrient loads as well as the volumes.	See the responses to Comments 69 and 84.

Comment Number	Date	Entity	Comment	Response
94	8/17/17	Member of Audience	(Member of Audience): I think you need to get the data from FDEP on TMDLs, because TMDLs can be a greater constraining factor for the health of the estuary, than the salinity.	FDEP uses our monthly CRE monitoring station data in addition to their own data.
95	8/30/17 8/17/17	Southwest Florida Watershed Council	Formulating a numeric target based on a midpoint of less than 400 cubic feet per second (cfs) is inconsistent with the concept of significant harm. It is inconsistent to develop a flow level based on a mid-point of multiple species rather than a mid-point on the most sensitive species for which data is available. The method used by the District to compute the mid-point does not avoid significant harm. (Noel Andress, Southwest Florida Watershed Council): We have on the books currently an MFL for the Caloosahatchee River of 300 cfs. That's good to talk about, let's get a scientific basis for what we really need in terms of the health of the estuary. When we can't even supply what the law calls for now, how in the world are we going to set a new number and expect any different results?	The comment is acknowledged.
96	8/30/17 8/17/17	Southwest Florida Watershed Council	The numeric targets selected by the District do not appear to meet the requirements of Florida statutes to avoid significant harm. Selecting targets that allow exceedances in salinity for a period > 55 days could lead to any number of 54-day periods separated by only one day. The target duration and recurrence period should be adjusted to read a salinity of 10 ppt shall not be permitted for more than 55 days in a 365 day period and at most two 55 day periods per five year period, to ensure a sufficient recovery period for seagrass and other species under high salinity conditions. (Noel Andress, Southwest Florida Watershed Council): The 55-day period is questionable since it would allow the counter to be reset after one release to the estuary. I will send you [Dr. Pinckney] our data.	(Dr. Pinckney): If you have alternative information to suggest another period [other than 55 days], I would be interested in seeing it. The flushing time of the CRE is approximately two months under very low inflow. This is the appropriate time scale to see high salinity effects on tape grass.
97	8/30/17 8/17/17	Southwest Florida Watershed Council	The District is using outdated population census and BEBER and species data that are several years out of date. Utilizing outdated information does not achieve the goal of evaluating current conditions based on new information and changing resource conditions. (Noel Andress, Southwest Florida Watershed Council): One of the components of the model is land use. I currently serve as the Chairman of the Lee County Local Planning Agency. We have, in the last couple of years, approved thousands of new units in the County. I don't understand why we would be using in our	<u>Existing Condition:</u> Surface water demands in the CRE area were modeled using 2012 land use data and the Lake Okeechobee Service Area Ledger as of February 2012 (consumptive use permits for surface water in the Lake Okeechobee Service Area [LOSA]). <u>Future Condition:</u> Surface water demands in the CRE area were modeled using 2012 land use data from the Existing Condition updated with county comprehensive plans and the Florida Department of Agriculture & Consumer Services' Florida Statewide Agricultural Irrigation Demand Geodatabase (FSAID)

Comment Number	Date	Entity	Comment	Response
			model, to try to come up with the impacts the population is going to have on the environment, with [data or information] that is 10 years in the past, when the county is one of the fastest growing counties in the U.S. (Noel Andress, Southwest Florida Watershed Council): I don't understand how we can look at the health of the estuary and *Vallisneria*, with your last data presented being from 2008. What is the current health of the estuary? We have had major events that have occurred in the last two years to the river.	database for crop projections. Nicodemus Slough was removed in the future condition since it was hydrologically disconnected from the LOSA basin as of 2015. By statute, the District uses a 20-year planning horizon to evaluate the future condition. In this instance, the 2040 demands were projected using the models to ensure the MFL would still be met with the recovery strategy in place.
98	8/30/17 8/17/17	Southwest Florida Watershed Council	The MFL is not meant to be a stand-alone resource protection tool. The consumptive use permitting program is supposed to be implemented to prevent harm to the water resources. There have been several violations of the MFL rule since the initial rule adoption in 2001. Sections 373.042 and 373.0421 are meant to reduce further withdrawals from permitted users to meet the MFL and avoiding serious harm to the water resource. (Noel Andress, Southwest Florida Watershed Council): The MFL has been a problem in the past because we have had during drought periods, and the water is not released to the estuary. All of the consumptive use permits issued…and there have been more CUPs here in this South Florida Water Management District than there is water available. It is over allocated currently. When we have a drought event, what we see suffering is the estuary itself, because the estuary doesn't get the water. It is at the bottom of the totem pole.	See the response to Comment 66.
99	8/30/17 8/17/17	Southwest Florida Watershed Council	We have been promised for many years a reservation for the protection of fish and wildlife or public health and safety as allowed in Section 373.223(4). No progress has been made on setting a reservation for the Caloosahatchee watershed to protect resources specifically required by Florida law. (Noel Andress, Southwest Florida Watershed Council): There's no reservation, like in Colorado, you have a reservation for the river so that you can assure that the MFL is going to be there. You can't assure that the MFL will be there without a reservation, and that's what we have.	See the response to Comment 79. A prospective water reservation rule [40E-10 .041(3), F.A.C.] was established for the C-43 Reservoir in 2014 to ensure that the future water stored in the reservoir is protected. This reservation also allowed the District to enter into a partnership agreement with the federal government to receive a 50-50 costs share and congressional authorization and appropriation.
100	8/30/17 8/17/17	Southwest Florida Watershed Council	It is difficult to set a MFL to prevent significant harm if water quality is not part of a prevention strategy. The District needs to work with FDEP to incorporate water quality data with water quantity data for a meaningful MFL for the	See the responses to Comments 6A1, 6C, 84 and 89.

Comment Number	Date	Entity	Comment	Response
			Caloosahatchee. The FDEP has water quality data for the Caloosahatchee river and watershed which needs to be included in developing an adequate MFL to prevent significant harm to aquatic species. (Noel Andress, Southwest Florida Watershed Council): I don't know how we can consider developing an MFL for a healthy estuary when we don't take into account the effect of the relationship between TMDLs and MFLs. The FDEP, in the 2006-2008 period, classified almost every waterbody in Florida, and almost every waterbody was impaired for a particular component or another, one chemical or another. Now, we have a problem in the State occurring currently, because we have what's called shifting baselines. All the waterbodies were impaired, we couldn't have that, I mean we can't stop economic development, so therefore we go back and reclassify all of the different parameters that we're using to say that a waterbody is impaired. (Noel Andress, Southwest Florida Watershed Council): Attached is an article written by TCPalm that recently was published in the Fort Myers, FL News-Press (U.S. Sugar Holds Sway on Policy, Lucas Daprile, USA Today Network-Florida, Sept. 3, 2017). I think this article explains why many in our community are skeptical regarding science based solutions to prevent significant harm to our estuary. I mentioned in my public comments the shifting baseline utilized by the FDEP and the SFWMD in establishing meaningful policies to address the health of our estuary. The article goes on to say the peer review of their polices did not indicate any problems. Hopefully the current Peer Review Group will speak out and not be a party to a MFL policy that does not prevent significant harm to the estuary.	
101	8/30/17	Southwest Florida Watershed Council	The District has expressed that they are not concerned with amount of nitrogen loading in formulating a MFL for the Caloosahatchee. How can you not consider both quantities of fresh water and nutrient loading when you are looking to set a policy to protect water resources and ecology from significant harm?	The statute that requires MFLs to be established (Chapter 373.042, Florida Statutes [F.S.]) is focused on water quantity or a minimum lake stage and minimum flow. Section 303(D) of the Federal Clean Water Act , and the parallel state rules for impaired waters and TMDLs (Chapters 62-303 and 62-304, F.A.C.), which are focused on water quality, both have different purposes.
102	8/30/17	Southwest Florida Watershed Council	There are no real time data on water quality or water levels in the draft report.	See the response to Comment 101.

Comment Number	Date	Entity	Comment	Response
103	8/30/17	Southwest Florida Watershed Council	The report does not discuss the harm caused to the estuary from high flows which can be more destructive than low flows.	Section 373.042, F.S. requires the District to evaluate MFLs to prevent significant harm, not evaluate high flows (discharges). Harm from high flows were not evaluated as part of this MFL reevaluation.
104	8/30/17 8/17/17	Southwest Florida Watershed Council	MFL report should incorporate more observed data into their predicted model data. (Noel Andress, Southwest Florida Watershed Council): All of this needs to be considered when we're looking at these models because we have models that were released from the District itself that show different results than those that have been presented here today. I would like everyone to make sure that we're going to look at accurate data when we start coming up with numbers, and we talk about how we're actually going to get the water to do the purpose that we're talking about.	South Florida Water Management Model (SFWMM) calibration statistics can be found in documentation at the following link: www.sfwmd.gov/sites/default/files/documents/sfwmm_final_121605.pdf The C-43 Reservoir Model is a simple water budget model that takes flows through S-79 from the SFWMM and redistributes them. No calibration is necessary for this model. It was peer reviewed by the USACE during the C-43 Reservoir project formulation. The CH3D model was calibrated using more than 10 years of long-term monitoring data. This should be adequate in most circumstances.
105	8/30/17	Southwest Florida Watershed Council	A study of a low salinity benthic species would be meaningful to establish an MFL to prevent significant harm of that species instead of taking a mid-point of several species which numeric criteria might not prevent significant harm to the resource.	The suggestion is acknowledged.
106	8/30/17	Southwest Florida Watershed Council	There are no penalties for violation of the MFL rule and past violations have not triggered reduced withdrawals from consumptive use permits for Phase I, II, or III water restrictions as required by MFL rules.	Florida statutes require existing legal users to reduce their allocations based on the type of water restrictions implemented. Also see the responses to Comments 39 and 46.
107	8/30/17	Southwest Florida Watershed Council	There are tools available to minimize harm due to low flows instead of a blanket statement that District can do nothing until C-43 reservoir is constructed.	The District, along with other stakeholder groups, evaluates the needs of the estuary on a weekly basis using real-time monitoring data and modeling to make flow recommendations for the CRE to the USACE.
108	8/30/17 8/17/17	Southwest Florida Watershed Council	The C-43 reservoir does not have a water quality component so relying on that water to meet the MFL may not be permitted. (Noel Andress, Southwest Florida Watershed Council): We have a problem currently of almost 2.5 million cfs of water annually is released to tide. We're talking here about a reservoir for 170,000 cfs [Note: It is actually 170,000 acre-feet] that doesn't come anywhere near addressing the problem in terms of the amount of water that's being released during the wet season. Therefore, it is really difficult to talk about the health of the estuary, when we're only looking at the MFL.	See the responses to Comments 40, 69, 100, and 101.

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APPENDIX C: MODEL DOCUMENTATION FOR EXISTING AND FUTURE SCENARIOS FOR THE CALOOSAHATCHEE RIVER ESTUARY MINIMUM FLOW CRITERIA REEVALUATION

OVERVIEW

Identification

This appendix documents assumptions and results for the existing and future scenario simulations used for the Caloosahatchee River Estuary (CRE) minimum flows and minimum water levels (MFL) reevaluation. The Existing Condition Baseline (ECB) and Future Condition Baseline (FCB) simulations are identical except for changes in the FCB, which include 2040 projected irrigation demands in the Caloosahatchee East, Caloosahatchee West, and S-4/Disston subwatersheds; and the operation of both the C-44 Reservoir along the St. Lucie Canal and the A-1 Reservoir within the Everglades Agricultural Area (EAA). These projects affect Lake Okeechobee water levels.

Scope and Objectives

The South Florida Water Management District (SFWMD or District) team determined the appropriate modeling techniques to be used given the scale and previous formulation of the model and consistent with a reasonable use of the South Florida Water Management Model (SFWMM; SFWMD 2005) based on best professional judgment and established peer review findings (Bras et al. 2005). The SFWMM was used to produce the starting point ECB and FCB.

The C-43 Reservoir Model is the accepted tool for use in scoping the Caloosahatchee River (C-43) West Basin Storage Reservoir (C-43 Reservoir) as part of the MFL reevaluation, it was reviewed and used for the development of the project implementation report (PIR) as part of the Comprehensive Everglades Restoration Plan (CERP; USACE and SFWMD 2010). A screening-level analysis was performed using the minimum flows of 300, 365, 380, 400, 450, and 650 cubic feet per second (cfs). For each simulation, the minimum operations for release criteria were set from 0 cfs to each of the values listed. The six daily sets of flows at the S-79 structure were delivered to the evaluation team and the team chose 300 and 400 cfs to evaluate further. These simulations were then finalized and are documented here.

Operational Intent

The intent of these model simulations was to represent existing infrastructure, operations, and restoration projects in the system with 2012 consumptive use demands compared to a future condition with projected Caloosahatchee East and Caloosahatchee West subwatersheds demands and future projects affecting Lake Okeechobee water levels. From these two starting points, the C-43 Reservoir is modeled using two different minimum flows (300 and 400 cfs) for the CRE through the S-79 structure.

Intended Use of Results

The SFWMM results assist in evaluating the regional and local effects of the relative change between the existing and future demand sets and projects designed to help restore natural systems. The C-43 Reservoir Model assists in evaluating the ability of this CERP project to maintain minimum flows to the estuary and provide beneficial timing of those flows. Subsequent models then take the updated S-79 flows and analyze salinity changes, which have the potential to impact the estuary.

BASIS

Assumptions

Two baselines of Agricultural Field Scale Irrigation Requirements Simulation/Water Balance (AFSIRS/WATBAL) were simulated to produce time series of East Caloosahatchee, West Caloosahatchee, and Disston/S-4 subwatersheds demand and runoff (existing and future) from 1965 to 2005 (**Figure C-1**). These time series were then used in two SFWMM bases to represent an ECB and FCB. The SFWMM then simulates the regional system, including Lake Okeechobee and its daily operations using the Lake Okeechobee Regulation Schedule of 2008 (LORS2008; USACE 2008). From the SFWMM, a baseline time series of flows at the S-79 structure are extracted. The S-79 data is used as input to the C-43 Reservoir Model (a spreadsheet model), which sends these flows to the reservoir when there is available storage and sends flows from the reservoir to the S-79 structure during drier times. The reservoir is modeled as in the CERP with minor changes to minimum deliveries for the MFL: 300 cfs and 400 cfs. **Attachment C-1** provides a full list of the SFWMM assumptions.

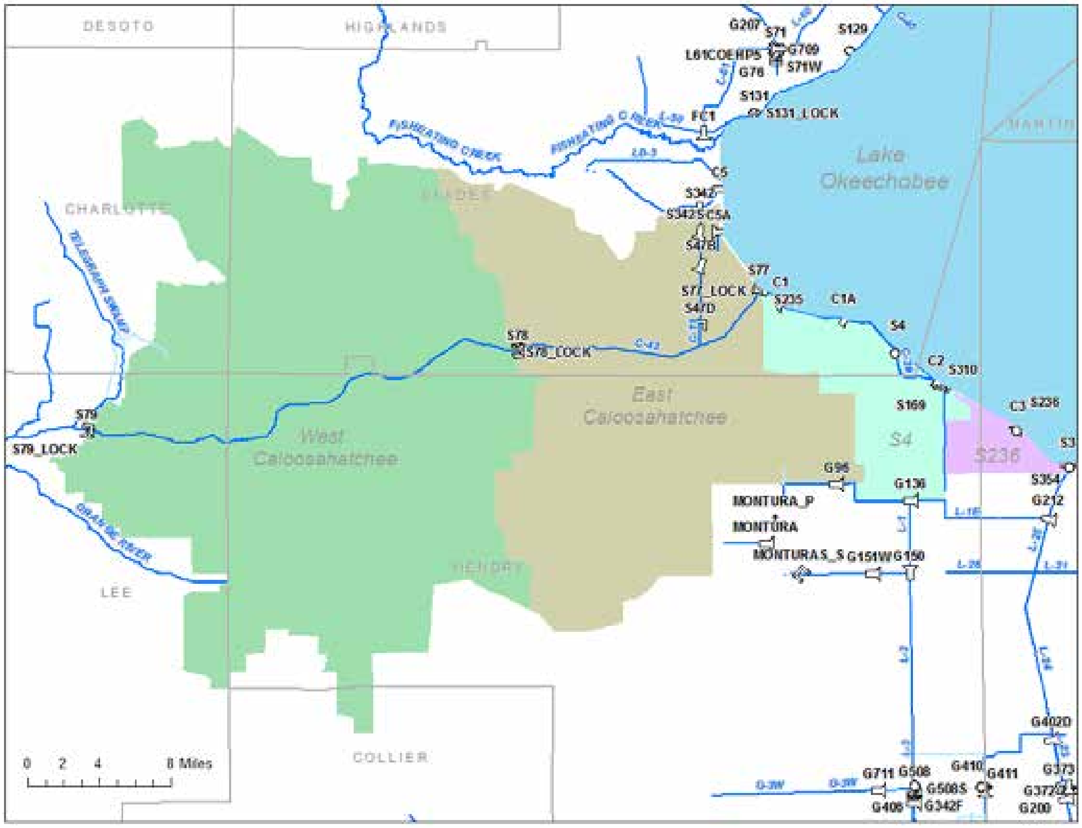

Figure C-1. The model domain of the AFSIRS/WATBAL hydrologic model for the CRE MFL.

The SFWMM receives output from the AFSIRS/WATBAL model in watersheds surrounding Lake Okeechobee known as the Lake Okeechobee Service Area (LOSA; **Figure C-2**). AFSIRS/WATBAL is a watershed-scale, simple water budget model based on the Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS; Smajstrla 1990). The CRE implementation of AFSIRS/WATBAL has been updated and includes ECB and FCB scenarios for this effort.

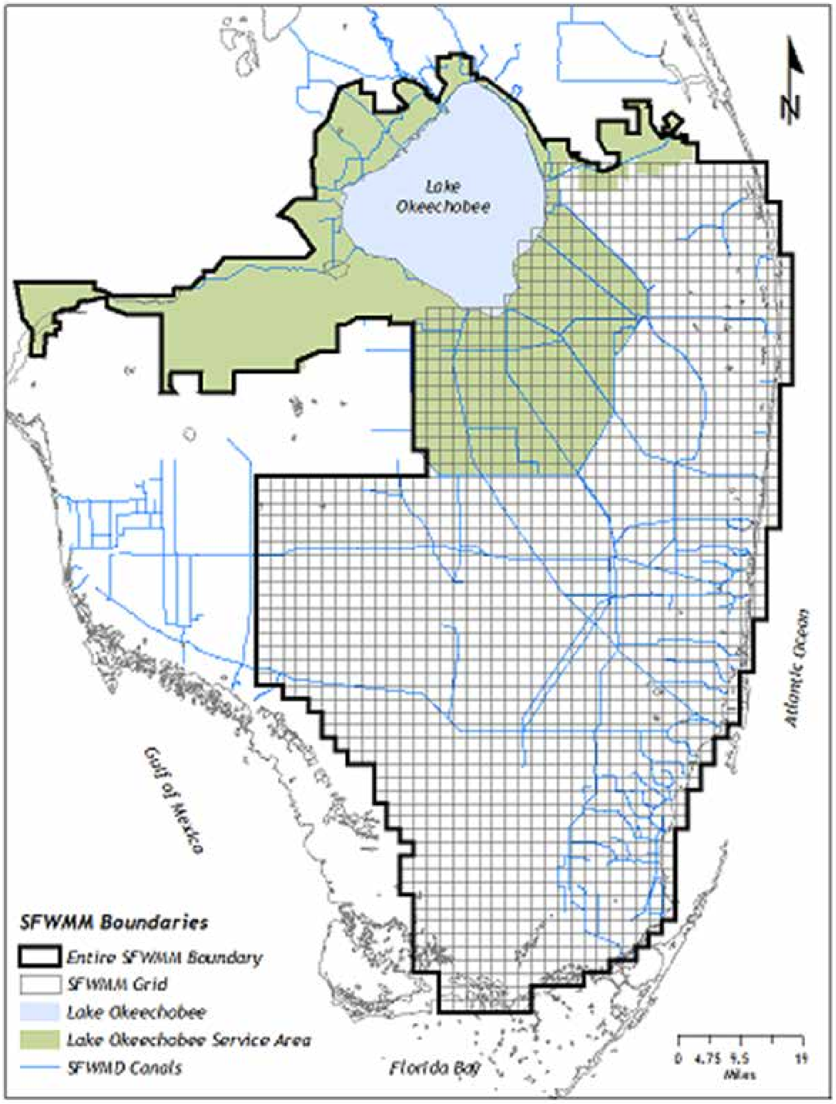

Figure C-2. The SFWMM boundary.

Current Demands (2012)

Demands for the CRE MFL Watershed were estimated using LOSA permitted water use boundaries from the *Lake Okeechobee Service Area Consumptive Use Demands for the South Florida Water Management Model* document (SFWMD 2012). These water use boundaries were those as of February 2012. Using ArcGIS, the permit boundaries with actual planted acreages were combined with land use information to estimate the acreages of agriculture in production. Current CERP project boundaries were also included to represent areas not in agricultural production. The data was then divided into the model subwatersheds and the AFSIRS/WATBAL model was updated and run. See **Table C-1** for a summary of land use types modeled in AFSIRS/WATBAL.

Table C-1. AFSIRS/WATBAL modeled acreages for the CRE MFL Watershed.
(Note: Nicodemus Slough Basin is not included in the 2040 acreages.)

	Modeled Acreage					
Year	**Citrus**	**Cane**	**Vegetable**	**Pasture**	**Upland Forest**	**Wetland**
2012	76,235	97,501	13,891	257,026	95,847	99,921
2040	83,584	106,255	7,310	248,026	68,452	85,897

Future Demands (2040)

Future (2040) irrigation projections for the East Caloosahatchee, West Caloosahatchee, and Tidal Caloosahatchee subwatersheds were developed using a combination of permit boundaries, public lands, county comprehensive plans and Florida Statewide Agricultural Irrigation Demand data. Current land use, updated to 2012, was used as the base land use geographic information system (GIS) layer. The Nicodemus Slough Basin was removed due to a change in its hydrologic connection to the East Caloosahatchee Subwatershed. Each of the listed data sets were incorporated into the 2012 land use data set and used to query and establish future land use Florida Land Use, Cover, and Forms Classification System (FLUCCS) codes for urban, conservation, water storage, and agriculture land use types. The data was then divided into the model subwatersheds and the AFSIRS/WATBAL model was updated and run. See **Table C-1** for a summary of land use types modeled in AFSIRS/WATBAL.

The FCB contains a 29,617-acre flow equalization basin (FEB) located north of Stormwater Treatment Area (STA) 3/4 and the Holey Land Wildlife Management Area. The total footprint represents the original 15,853-acre A-1 FEB footprint plus the additional 13,764-acre A-2 FEB footprint. The FCB also simulates the C-44 Reservoir which is 9,315 acres at 4.85 foot depth to limit high flows from the surrounding basins to the St. Lucie River Estuary and to meet basin water supply demands.

Model Limitations

The SFWMM is a robust and complex regional-scale model. Due to the scale of the model, it is frequently necessary to implement abstractions of system infrastructure and operations that will, in general, mimic the intent and result of the desired project features while not matching the exact mechanism by which these results would be obtained in the real world. Additionally, it is sometimes necessary to work within established paradigms and foundations within the model code (e.g. use available input-driven options to represent more complex project operations).

The C-43 Reservoir Model is not a complex hydrodynamic model. Its primary goal is to compare the CERP with-project discharge from S-79 (the downstream point at which the CRE MFL Watershed discharges into the estuary) to both the preproject discharge over S-79 for a daily time step. In addition, the model also shows a water budget for the reservoir and tracks reservoir inflows, releases, and storage.

SIMULATION

Modeling Tools Used

The modeling tools used are summarized below:

- AFSIRS/WATBAL
  - Model Location: \\ad.sfwmd.gov\dfsroot\data\hesm_arch1\projects\c43_mfl_update_2016\models\afsirs
- SFWMM version 6.6.5
  - Model Executable Location: /nw/hesm_san/oom/sfwmm/apps/wmm/prod/sfwmm/rel-6-6-5/wmm.exe
- C-43 Reservoir Model
  - Model Location: \\ad.sfwmd.gov\dfsroot\data\hesm_arch1\projects\c43_mfl_update_2016\models\reservoir

Model Set Up

Source data for the ECB and FCB simulations can be found at \\ad.sfwmd.gov\dfsroot\data\hesm_arch1\projects\lecwsp2012\models\sfwmm\LEC2013_WMM6.6.5_2010_042913_in.

Structural and Physical Additions/Modifications

The ECB without Reservoir simulation is the LEC2013_WMM6.6.5_2010_042913_in simulation. Changes were made to this simulation to produce the FCB without Reservoir simulation. These changes include the following:

- 2040 projected East Caloosahatchee, West Caloosahatchee, and S-4 and Disston subwatersheds demand and runoff time series
- C-44 Reservoir along the St. Lucie Canal
- A-1 Reservoir within the EAA

Once the SFWMM is complete (baseline S-79 flows) the C-43 Reservoir Model is run with the operations found in **Tables C-2** and **C-3** to produce four modified S-79 time series for evaluation by the CRE MFL Team.

Table C-2. Operations for the ECB and FCB 300-cfs minimum flow reservoir simulations.

Fill (Limit 1500 cfs)			Pump			
WL In Reservoir			Wet Season - Early	Late Wet season	Dry Season - Early	late Dry season
	S-79 Flows	Code	EW	LW	ED	LD
Empty	520.01	1	0	0	0	0
Empty	650.01	2	0	200	150	150
Empty	850.01	3	0	250	250	250
Empty	1000.01	4	250	350	350	350
Empty	1200.01	5	400	500	500	500
Empty	1500.01	6	750	800	700	700
Empty	2000.01	7	850	1250	1000	1000
Empty	2800.01	8	1150	1500	1500	1500
Empty	99999	9	1500	1500	1500	1500
END	S-79 Flows	Code	EW	LW	ED	LD
Medium	520.01	1	0	0	0	0
Medium	650.01	2	0	200	0	0
Medium	850.01	3	0	250	200	0
Medium	1000.01	4	250	350	300	0
Medium	1200.01	5	400	500	450	0
Medium	1500.01	6	680	800	700	0
Medium	2000.01	7	750	1250	1000	750
Medium	2800.01	8	950	1500	1500	1000
Medium	99999	9	1500	1500	1500	1500
END	S-79 Flows	Code	EW	LW	ED	LD
Full	520.01	1	0	0	0	0
Full	650.01	2	0	0	0	0
Full	850.01	3	0	250	0	0
Full	1000.01	4	0	350	200	0
Full	1200.01	5	0	450	400	0
Full	1500.01	6	350	700	700	0
Full	2000.01	7	500	900	900	500
Full	2800.01	8	800	1200	1250	800
Full	99999	9	1500	1500	1500	1500

Release (Limit 1200 cfs)			Gravity			
WL In Reservoir			Wet Season - Early	Late Wet season	Dry Season - Early	late Dry season
	S-79 Flows	Code	EW	LW	ED	LD
Empty	200.01	1	300	300	300	300
Empty	300.01	2	0	0	0	0
Empty	400.01	3	0	0	0	0
Empty	550.01	4	0	0	0	0
Empty	800.01	5	0	0	0	0
Empty	1000.01	6	0	0	0	0
Empty	1500.01	7	0	0	0	0
Empty	2800.01	8	0	0	0	0
Empty	99999	9	0	0	0	0
END	S-79 Flows	Code	EW	LW	ED	LD
Medium	200.01	1	1050	400	400	650
Medium	300.01	2	850	225	250	550
Medium	400.01	3	650	100	50	450
Medium	550.01	4	400	0	0	450
Medium	800.01	5	250	0	0	200
Medium	1000.01	6	0	0	0	0
Medium	1500.01	7	0	0	0	0
Medium	2800.01	8	0	0	0	0
Medium	99999	9	0	0	0	0
END	S-79 Flows	Code	EW	LW	ED	LD
Full	200.01	1	1150	450	450	850
Full	300.01	2	1050	350	350	800
Full	400.01	3	850	350	350	700
Full	550.01	4	650	350	350	700
Full	800.01	5	500	0	0	500
Full	1000.01	6	350	0	0	350
Full	1500.01	7	150	0	0	150
Full	2800.01	8	0	0	0	0
Full	99999	9	0	0	0	0

Table C-3. Operations for the ECB and FCB 400-cfs minimum flow reservoir simulation.

Fill (Limit 1500 cfs)			Pump			
WL In Reservoir			Wet Season - Early	Late Wet season	Dry Season - Early	late Dry season
	S-79 Flows	Code	EW	LW	ED	LD
Empty	520.01	1	0	0	0	0
Empty	650.01	2	0	200	150	150
Empty	850.01	3	0	250	250	250
Empty	1000.01	4	250	350	350	350
Empty	1200.01	5	400	500	500	500
Empty	1500.01	6	750	800	700	700
Empty	2000.01	7	850	1250	1000	1000
Empty	2800.01	8	1150	1500	1500	1500
Empty	99999	9	1500	1500	1500	1500
END	S-79 Flows	Code	EW	LW	ED	LD
Medium	520.01	1	0	0	0	0
Medium	650.01	2	0	200	0	0
Medium	850.01	3	0	250	200	0
Medium	1000.01	4	250	350	300	0
Medium	1200.01	5	400	500	450	0
Medium	1500.01	6	680	800	700	0
Medium	2000.01	7	750	1250	1000	750
Medium	2800.01	8	950	1500	1500	1000
Medium	99999	9	1500	1500	1500	1500
END	S-79 Flows	Code	EW	LW	ED	LD
Full	520.01	1	0	0	0	0
Full	650.01	2	0	0	0	0
Full	850.01	3	0	250	0	0
Full	1000.01	4	0	350	200	0
Full	1200.01	5	0	450	400	0
Full	1500.01	6	350	700	700	0
Full	2000.01	7	500	900	900	500
Full	2800.01	8	800	1200	1250	800
Full	99999	9	1500	1500	1500	1500

Release (Limit 1200 cfs)			Gravity			
WL In Reservoir			Wet Season - Early	Late Wet season	Dry Season - Early	late Dry season
	S-79 Flows	Code	EW	LW	ED	LD
Empty	200.01	1	400	400	400	400
Empty	300.01	2	100	100	100	100
Empty	400.01	3	0	0	0	0
Empty	550.01	4	0	0	0	0
Empty	800.01	5	0	0	0	0
Empty	1000.01	6	0	0	0	0
Empty	1500.01	7	0	0	0	0
Empty	2800.01	8	0	0	0	0
Empty	99999	9	0	0	0	0
END	S-79 Flows	Code	EW	LW	ED	LD
Medium	200.01	1	1050	400	400	650
Medium	300.01	2	850	225	250	550
Medium	400.01	3	650	100	50	450
Medium	550.01	4	400	0	0	450
Medium	800.01	5	250	0	0	200
Medium	1000.01	6	0	0	0	0
Medium	1500.01	7	0	0	0	0
Medium	2800.01	8	0	0	0	0
Medium	99999	9	0	0	0	0
END	S-79 Flows	Code	EW	LW	ED	LD
Full	200.01	1	1150	450	450	850
Full	300.01	2	1050	350	350	800
Full	400.01	3	850	350	350	700
Full	550.01	4	650	350	350	700
Full	800.01	5	500	0	0	500
Full	1000.01	6	350	0	0	350
Full	1500.01	7	150	0	0	150
Full	2800.01	8	0	0	0	0
Full	99999	9	0	0	0	0

Operational Additions/Modifications

Within the SFWMM, all operations remain identical except for the inclusion of the A-1 Reservoir and C-44 Reservoir. The C-43 Reservoir Model uses the parameters in **Table C-4** and the values in **Tables C-2** and **C-3** for empty and fill operations. These options and operations are included in the CERP PIR (USACE and SFWMD 2010). Modifications were made to the release values to attempt to maintain minimum flows through S-79 of 300 cfs (**Table C-2**) and 400 cfs (**Table C-3**).

Table C-4. C-43 Reservoir options.

Reservoir Input Parameters		
Inflow pump capacity	1,500	cfs
Outflow capacity	1,200	cfs
Overflow capacity	5000	cfs
Tolerance for Spillage	0.3	ft
Initial Reservoir Storage	0	ac-ft

Additional Reservoir Parameters		
Footprint	9,380	ac
Max res heig	42.0	ft

Model Options	
Adjust runoff to S79 based on:	Accumulated RF/RO Rati
Operation criteria based on:	Seasonal/Res stage criter

RESULTS

Identification of Simulations

Simulations are as follows:

- ECB using the SFWMM: \\ad.sfwmd.gov\dfsroot\data\hesm_nas\projects\c43_mfl_update_2016\models\sfwmm\LEC2013_WMM6.6.5_2010_042913_out
- ECB with the C-43 Reservoir operational and a 300-cfs minimum flow to the estuary: \\ad.sfwmd.gov\dfsroot\data\hesm_nas\projects\c43_mfl_update_2016\models\reservoir\C43_PIR-model_v2.0_MFL_sfwmm_300cfs_ecb_final.xlsm
- ECB with the C-43 Reservoir operational and 400-cfs minimum flow to the estuary: \\ad.sfwmd.gov\dfsroot\data\hesm_nas\projects\c43_mfl_update_2016\models\reservoir\C43_PIR-model_v2.0_MFL_sfwmm_400cfs_ecb_final.xlsm
- FCB using the SFWMM: \\ad.sfwmd.gov\dfsroot\data\hesm_nas\projects\c43_mfl_update_2016\models\sfwmm\FWO1.0_WMM6.6.5_022017_out
- FCB with the C-43 Reservoir operational and 300-cfs minimum flow to the estuary: \\ad.sfwmd.gov\dfsroot\data\hesm_nas\projects\c43_mfl_update_2016\models\reservoir\C43_PIR-model_v2.0_MFL_sfwmm_300cfs_fcb_final.xlsm
- FCB with the C-43 Reservoir operational and 400-cfs minimum flow to the estuary: \\ad.sfwmd.gov\dfsroot\data\hesm_nas\projects\c43_mfl_update_2016\models\reservoir\C43_PIR-model_v2.0_MFL_sfwmm_400cfs_fcb_final.xlsm

Regional-level Results

On a regional scale, the projected changes that affect Lake Okeechobee were modeled in the FCB. The Central Everglades Planning Project (CEPP) will send an additional 20,000 acre-feet per year of water south to the Everglades and, as a result, Lake Okeechobee water levels are expected to be lowered. The A-1 Reservoir within the EAA was modeled and sends this amount of water south.

Lake Okeechobee

Lake Okeechobee plays a major role in the regional water supply system of southeast Florida. Large changes in water levels in Lake Okeechobee have regional affects downstream. In the FCB the water levels in Lake Okeechobee are decreased (**Figure C-3**) due to increased volumes of Lake Okeechobee water being sent south to the Everglades (20,000 acre-feet per year). This reduces the amount of available water for the Caloosahatchee River and St. Lucie estuaries. During wet times this is beneficial but during drier times it may limit what can be sent to the estuaries to avoid high salinity conditions.

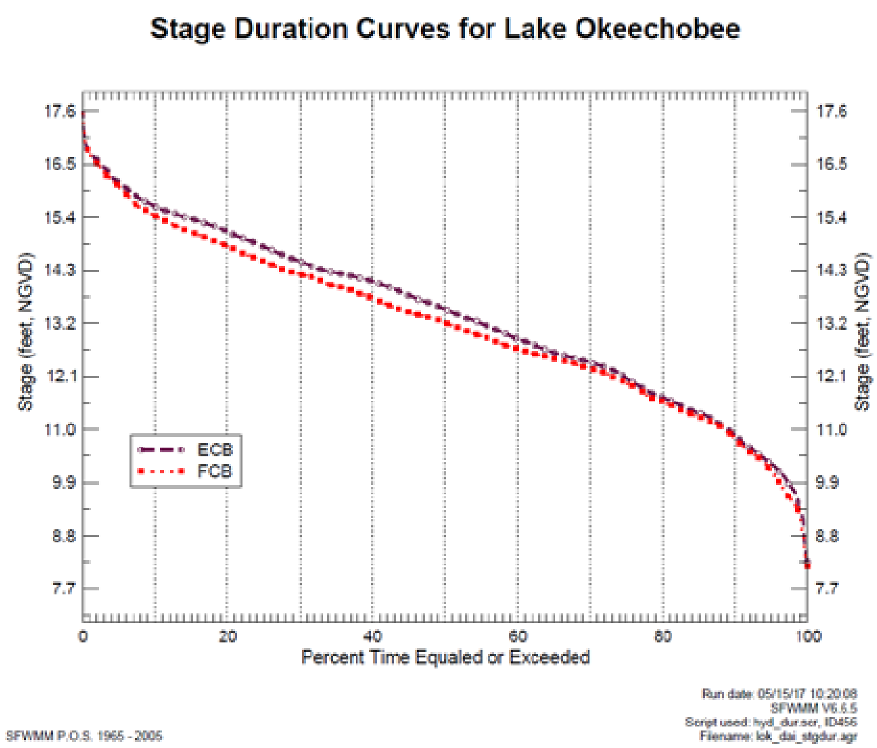

Figure C-3. SFWMM Lake Okeechobee results for ECB and FCB.
(Note: NGVD – National Geodetic Vertical Datum of 1929.)

Local-level Results

As part of CERP, the C-43 Reservoir is intended to provide relief for the CRE by capturing some of the wet season flows and providing additional flows during the dry season to provide a more consistent salinity regime. When water is abundant, it can be stored and recovered during drier times. The reservoir is 9,380 acres and operates between 19.24 and 42.00 feet National Geodetic Vertical Datum of 1929 (NGVD29). Two operational changes were made from the original operations in the CERP PIR (USACE and SFWMD 2010), 300- and 400-cfs minimum flows to the CRE. For each of these operational changes, there is an existing and a future simulation, each using the SFWMM scenario S-79 flow as input. Below are the results for S-79 flows as modified by the C-43 Reservoir Model, the "Base" is the original SFWMM S-79 flows and the "with Project" flows are with the C-43 Reservoir in place.

Figures C-4 through **C-7** illustrate the ability of the C-43 Reservoir to lower high discharge events that harm the estuary while maintaining a minimum flow for almost the entire 1965–2005 period of record. The use of the PIR restoration target time series is for reference, it is the future CERP restoration objective for the entire CRE MFL Watershed. This future restoration objective is outside of the scope of this MFL reevaluation. There was not an attempt to meet this target but the team can analyze the results with that as a comparison.

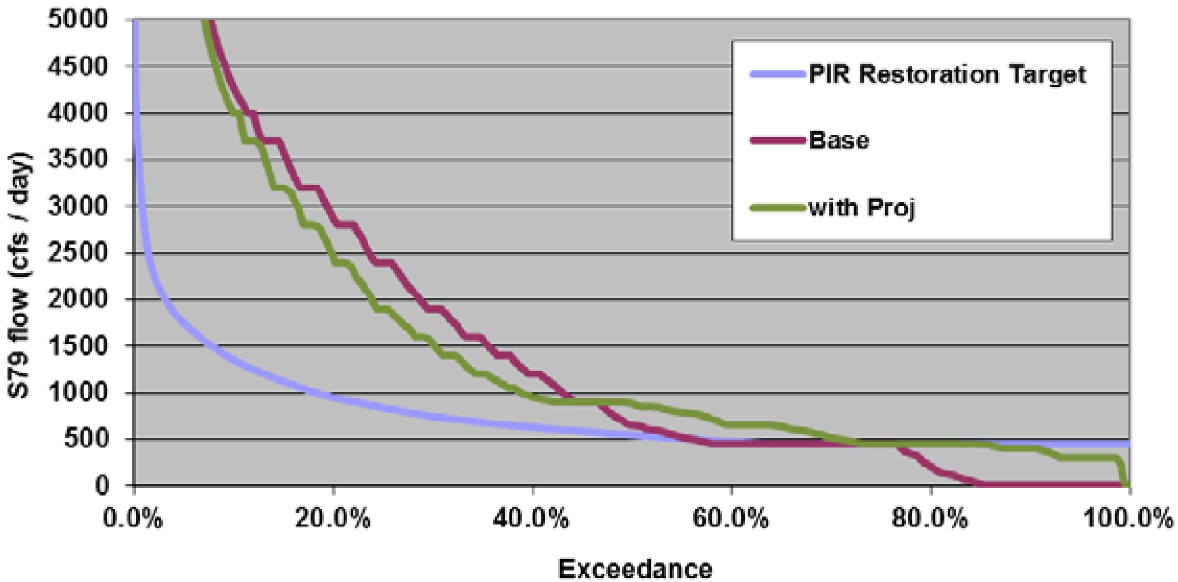

Figure C-4. Flow exceedance curves for the ECB Base and 300-cfs minimum simulations.

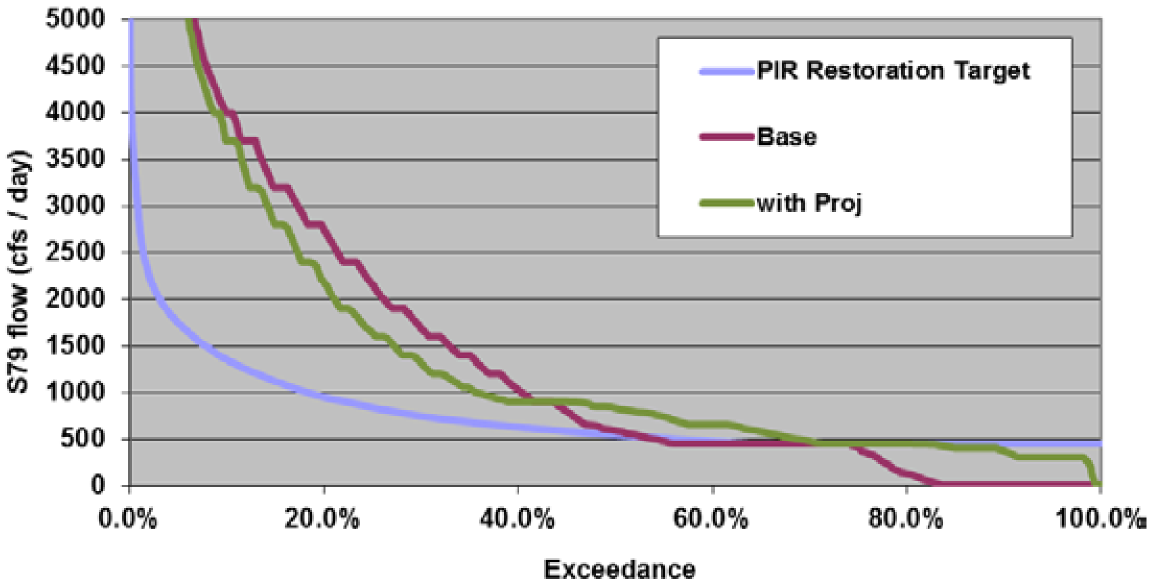

Figure C-5. Flow exceedance curves for the FCB Base and 300-cfs minimum simulations.

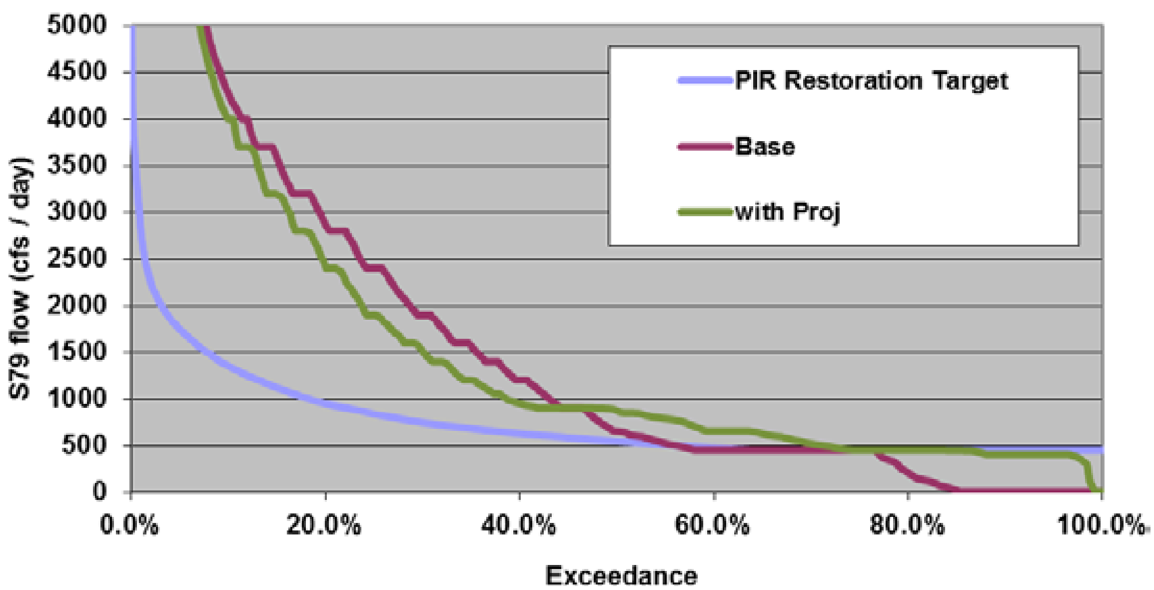

Figure C-6. Flow exceedance curves for the ECB Base and 400-cfs minimum simulations.

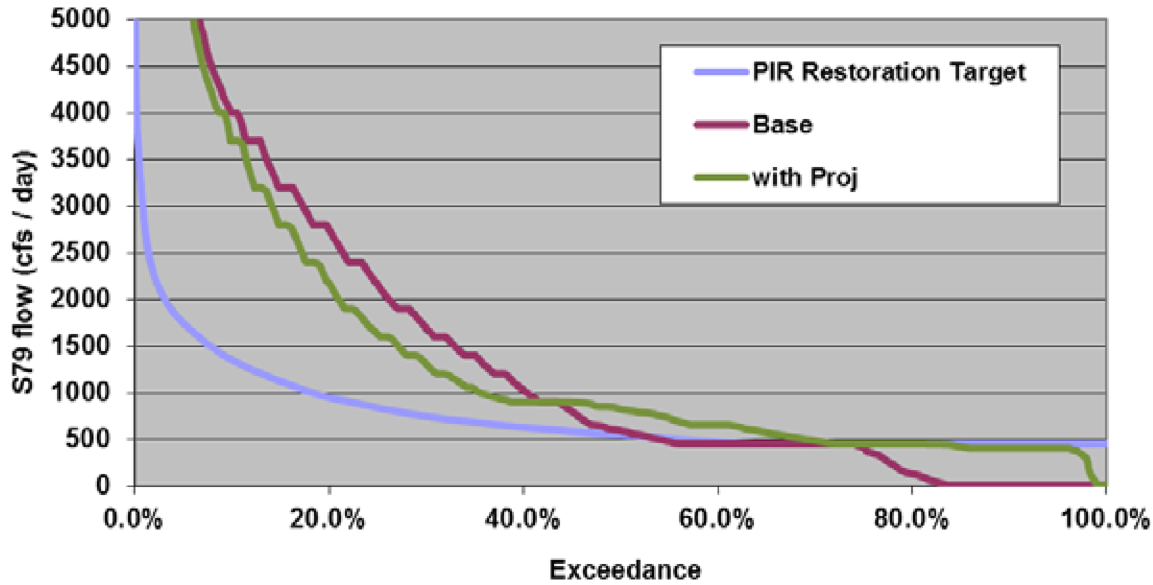

Figure C-7. Flow exceedance curves for the FCB Base and 400-cfs minimum simulations.

Achievement of Modeling Objectives

To understand the potential impacts of future land use and CERP/CEPP project changes to Lake Okeechobee and the CRE, the ECB and FCB simulations provide useful information. Future land use changes along with CERP/CEPP projects reduce the amount of water being sent to the estuary. The C-43 Reservoir will provide significant benefits to the CRE by reducing some of the high discharge flows during the wet season while meeting minimum flows during the dry season to provide a stable and consistent salinity regime.

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ATTACHMENT C-1: ASSUMPTIONS for THE SFWMM

	Existing Condition Baseline	Future Condition Baseline
Model & Climate	· Based on SFWMM version 6.6.5 and includes wet and dry season operation for forward pumps for Lake Okeechobee · Period of simulation is 1965–2005, model is calibrated for 1965–2000 (SFWMD 2005), and rainfall and evapotranspiration is extended for 2001–2005	Same as ECB
Topography	Updated November 2001 and September 2003 using latest available information (in NGVD29) November 2001 update (documented in November 2001 SFWMD memorandum from M. Hinton to K. Tarboton) includes the following: · United States Geological Survey (USGS) high accuracy elevation data from helicopter surveys collected 1999–2000 for Everglades National Park (ENP) and Water Conservation Area (WCA) 3 south of Alligator Alley · USGS light detection and ranging (LiDAR) data (May 1999) for WCA-3A north of Alligator Alley · Lindahl, Browning, Ferrari & Helstrom 1999 survey for Rotenberger Wildlife Management Area (WMA) · Everglades STAs surveys from 1990s · Aerometric Corporation 1986 survey of the 8.5 Square Mile Area · Includes estimate of Everglades Agricultural Area (EAA) subsidence · Other data as in SFWMM version 3.7 · Florida Fish and Wildlife Conservation Commission (FWC) survey 1992 for the Holey Land WMA September 2003 update includes the following: · Reverting to FWC 1992 survey data for Rotenberger WMA · DHI gridded data from Kimley-Horn contracted survey of EAA, 2002–2003, regridded to 2-mile by 2-mile scale for EAA outside of STAs and WMAs	Same as ECB

	Existing Condition Baseline	Future Condition Baseline
Sea Level	Sea level data from six long-term National Oceanic and Atmospheric Administration stations were used to generate a historic record to use as sea level boundary conditions for the 1965 to 2005 evaluation period	Same as ECB
Natural Area Land Cover (Vegetation)	Vegetation classes and their spatial distribution in the natural comes from the following data: · Walsh 1995 aerial photography in ENP · Rutchey 1995 classification in WCA-3B, WCA-3A north of Alligator Alley and the Miami Canal, WCA-2A, and WCA-2B · Richardson 1990 data for the Arthur R. Marshall Loxahatchee National Wildlife Refuge (LNWR) · Florida Land Use, Cover and Forms Classification System (FLUCCS 1995 for Big Cypress National Preserve, Holey Land & Rotenberger WMA, WCA-3A south of Alligator Alley, and Miami Canal (documented in August 2003 SFWMD memorandum from J. Barnes and K. Tarboton to J. Obeysekera)	Same as ECB
Land Use	· All land use in the Lower East Coast has been updated using most recent 2008–2009 Geographic Information System (GIS) Enterprise data	· County comprehensive land use plans · Florida Statewide Agricultural Irrigation Demand polygons used to project and inventory agricultural areas
Lake Okeechobee Service Area (LOSA) Basins Demands	· Lower Istokpoga, North Lake Shore, and Northeast Lake Shore demands and runoff based on AFSIRS modeling using LOSA permitted water use as of February 2012 (SFWMD 2012) · 1-in-10 demands updated	Same as ECB except, East Caloosahatchee, West Caloosahatchee, Tidal Caloosahatchee, S-4, and Disston subwatersheds updated to 2040 projections
Lake Okeechobee Operations	· LORS2008 thresholds according to bands within the Operational Management Band and its subbands according to its decision tree (USACE 2008) · Lake Okeechobee Water Shortage Management (LOWSM) guidelines are used to implement LOSA water restriction cutbacks as per rule 40E-21 and 40E-22, Florida Admistrative Code (F.A.C.); the LOSA triggering line is the line starting at 13.0 feet on October 1 and ending at 10.5 feet on May 31, with additional breakpoints defined in between · Emergency flood control backpumping to Lake Okeechobee from the EAA	Same as ECB

	Existing Condition Baseline	Future Condition Baseline
	· Lake Okeechobee best management practice (BMP) makeup water deliveries to WCAs are not made · Adaptive Protocols for Lake Okeechobee Operations surrogate based on flows and not salinity · Lake flood control releases under LORS2008 are allowed through the Miami and North New River canals into STA-3/4 to a maximum of 60,000 acre-feet per year · No LORS2008 baseflow deliveries to the St. Lucie Estuary (previously 200 cfs) · LORS2008 baseflow deliveries to CRE (450 cfs) · Variable deliveries to CRE to match target time series from Lake Okeechobee Operations Screening (LOOPS) modeling (0 to 650 cfs)	
Caloosahatchee River Basin and S-4 Basin	· Caloosahatchee River Basin irrigation demands and runoff were estimated using the AFSIRS method based on existing land use and LOSA permitted water use information as of February 2012 (SFWMD 2012) · Public water supply daily intake from the river is included in the analysis	· FSAID 3 data used to project agricultural lands · County comprehensive plans used to update urban land use types · Public-owned lands used for conservation lands · Nicodemus Slough Basin removed from East Caloosahatchee Subwatershed due to hydrologic changes
St. Lucie Canal Basin	· St. Lucie Canal Basin demands estimated using the AFSIRS method based on LOSA permitted water use · Basin demands include the Florida Power & Light Reservoir at Indiantown	Same as ECB
Everglades Agricultural Area	· EAA irrigation demands are simulated using climatic data for the 41-year period of record and a soil moisture accounting algorithm, with parameters calibrated to match historical regional supplemental deliveries from Lake Okeechobee · SFWMM EAA runoff and irrigation demand response to rainfall was calibrated for 1984–1995 and verified for 1979–1983/1996–2000; no runoff reduction adjustment was necessary to account for BMPs · Minimum elevation at which farmers can pump water out of the major canals for supplemental irrigation is 8.0 feet · Irrigated area of 458,240 acres per LOSA permitted water use as of February 2012 · 1-in-10 demands updated	Same as ECB

	Existing Condition Baseline	Future Condition Baseline
Brighton Seminole Indian Reservation Demands	· The 2-in-10 demand set forth in the Seminole Compact Work Plan[5] equals 2,262 million gallons per month (MGM); AFSIRS modeled 2-in-10 demands equaled 2,383 MGM · While estimated demands and therefore deliveries, for every month of simulation do not equate to monthly entitlement quantities as per Table 7, Agreement 41-21 (November 1992), tribal rights to these quantities are preserved[1] · LOWSM applies to this agreement	Same as ECB
Seminole Big Cypress Reservation Demands	· Big Cypress Reservation irrigation demands and runoff were estimated using the AFSIRS method based on existing planted acreage in a manner consistent with that applied to other basins not in the distributed mesh of the SFWMM · The 2-in-10 demand set forth in the Seminole Compact Work Plan[1] equals 2,606 MGM; AFSIRS modeled 2-in-10 demands equaled 2,659 MGM · While estimated demands, and therefore deliveries, for every month of simulation do not equate to monthly entitlement quantities as per the District's Final Order and Tribe's Resolution establishing the Big Cypress Reservation entitlement, tribal rights to these quantities are preserved · LOWSM applies to this agreement	Same as ECB
Seminole Hollywood Reservation Demands	· Estimated demands as listed in Table A-10 within Appendix A of the *2013 Lower East Coast Water Supply Plan Update* (SFWMD 2013a)	Same as ECB
Everglades Construction Project	· STA-1 West = 6,670 acres · STA-1 East = 4,994 acres · STA-2 = 8,243 acres · STA-3/4 = 16,327 acres · STA-5 = 6,165 acres · STA-6 = 2,763 acres · 45,162 acres of total treatment area · Operation of STAs assumes maintenance of a 6-inch minimum depth	Same as ECB, except a 29,617-acre FEB is located north of STA-3/4 and Holey Land WMA. The total footprint represents the original 15,853-acre A-1 Reservoir footprint plus the additional 13,764-acre A-2 Reservoir footprint operated as follows: · Assumed average topography of 9.63 feet NGVD29. FEB inflows are from excess EAA Basin runoff above the established inflow · Targets at STA-3/4, STA-2 North, and STA-2 South, and from Lake

[5] The work plan falls under the *Water Rights Compact among the Seminole Tribe of Florida, the State of Florida and the South Florida Water Management District*, which is available online at http://www.semtribe.com/services/water/Seminole%20Water%20Compact.pdf.

	Existing Condition Baseline	Future Condition Baseline
		Okeechobee flood releases south · FEB outflows are used to help meet established inflow targets at STA-3/4, STA-2 North, and STA-2 South if EAA Basin runoff and Lake Okeechobee flood releases are not sufficient · 0.5-foot minimum depth below which no releases are allowed · 3.8-foot maximum depth above which inflows are discontinued · No supplemental water supply provided to the FEB · Assumed inlet pump from STA-3/4 supply canal with capacity equal to combined capacity of G-372 and G-370 structures · Outflow weirs, with similar discharge characteristics as STA-3/4 outlet structure, discharging into lower Miami and lower North New River canals
Public Water Supply and Irrigation (non-LOSA)	· Public water supply wellfield withdrawals and locations are based on actual Biscayne aquifer withdrawal data for Calendar Year 2010 with monthly withdrawal patterns derived from 2006–2010 values (SFWMD 2013b) · Irrigation demands are based upon existing land use and calculated using AFSIRS, reduced to account for landscape and golf course areas irrigated using reuse water and landscape areas irrigated using public water supply (SFWMD 2013b)	Same as ECB
Coastal Basin Canal Facilities and Operations	· Central and Southern Florida Flood Control Project (C&SF Project) system and operating rules in effect in 2010 · Includes operations to meet control elevations in the primary coastal canals for the prevention of saltwater intrusion as per MFLs · Includes existing secondary drainage/ water supply system · C-11 Water Quality Treatment Critical Project (S-381 and S-9A) · South Dade Conveyance System operations will follow Everglades Restoration Transition Plan (ERTP)	Same as ECB

	Existing Condition Baseline	Future Condition Baseline
Western Basins	· Boundary flows calculated using C-139 Regional Simulation Model Basin Model, entered as flows for G-136, G-88, G-89, G-155, and USSO	Same as ECB
Big Cypress National Preserve	· Simulated demands in excess of historical demands are partially supplied by basin flows; any remaining excess water is directed to S-190 · Western Tamiami Trail culverts are not modeled in SFWMM due to the coarse (2-mile by 2-mile) model resolution	Same as ECB
WCA-1 (LNWR)	· Interim Regulation Schedule per United States Fish and Wildlife Service/LNWR; includes regulatory releases to tide through Lower East Coast Service Area (LECSA) canals · No net outflow to maintain minimum stages in the LECSA canals (salinity control), if water levels are less than minimum operating criteria of 14 feet · The bottom floor of the schedule (Zone C) is the area below 14 feet · Any water supply releases below the floor will be matched by an equivalent volume of inflow from Lake Okeechobee	Same as ECB
WCA-2A & WCA-2B	· Current C&SF Project regulation schedule, which includes regulatory releases to tide through LECSA canals · No net outflow to maintain minimum stages in the LECSA canals (salinity control), if water levels in WCA-2A are less than minimum operating criteria of 10.5 feet · Any water supply releases below the floor will be matched by an equivalent volume of inflow from Lake Okeechobee	Same as ECB
WCA-3A & WCA-3B	· Current C&SF Project regulation schedule for WCA-3A, as per Water Control Plan – Everglades Restoration Transition Plan – C&SF Project (USACE 2012) · Includes regulatory releases to tide through LECSA canals · No net outflow to maintain minimum stages in the LECSA canals (salinity control), if water levels are less than minimum operating criteria of 7.5 feet in WCA-3A · Any water supply releases below the floor will be matched by an equivalent volume of inflow from Lake Okeechobee	Same as ECB
Operations	· Releases from WCA-3A to ENP and the South Dade Conveyance System	Same as ECB

	Existing Condition Baseline	Future Condition Baseline
	follows the ERTP: o S-343A, S-343B, and S-344 are closed November through July o S-12A is closed January through July o S-12B is closed January through July o S-12C is not closed o S-12D is not closed	
Tamiami Trail Modifications (Modified Water Deliveries to Everglades National Park [MWD])	L-29 Canal maximum stage 7.5 feet	Same as ECB
Conveyance and Seepage Control Features (MWD)	Conveyance features: · Combined capacity of S-355A, S-355B, and S-356 = 2,500 cfs (January–June) · Combined capacity of S-355A, S-355B, and S-356 = 5,000 cfs (July–December)	Same as ECB
8.5 Square Mile Area Project (MWD)	No	Same as ECB
C-111 South Dade Project	S-332B, S-332C, and S-332D impoundments	Same as ECB
Northern Everglades and Estuaries Protection Program	No	Same as ECB
Restoration Strategies	No	Same as ECB
C-51 Reservoir Project	No	Same as ECB
Other	Kissimmee River inflows at S-65E represent: · Interim Operating Schedule for the Kissimmee Chain of Lakes using the Upper Kissimmee (UKISS) Model · UKISS Model flows adjusted by Sealink flows and historic data to more closely match land use practices	Same as ECB
ACME Basin B Discharge	ACME Basin B discharge to WCA-1 via STA-1 East	Same as ECB
Broward County Water Preserve Areas	No	Same as ECB

	Existing Condition Baseline	Future Condition Baseline
C-111 Spreader Canal	No	Same as ECB
Caloosahatchee River (C-43) West Basin Storage Reservoir	No	Same as ECB
C-44 Reservoir	No	9,315-acre reservoir with a 4.85-foot depth to meet basin water supply demands
ENP Seepage Management	No	Same as ECB
Loxahatchee River Watershed Restoration	· L-8 FEB in place but not operational · Indian Trails Improvement District Reservoir operational with upper basin runoff sent to reservoir, which discharges to the L-8 Canal	Same as ECB

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APPENDIX D: WASH MODEL DOCUMENTATION FOR THE TIDAL CALOOSAHATCHEE SUBWATERSHED

ABSTRACT

An estuary usually receives a significant amount of fresh water from its tidal basin. The amount of freshwater inflow to an estuary is a critical piece of information for managing the estuary for its ecosystem. Freshwater inflow to the Caloosahatchee River Estuary (CRE), Florida, from its tidal basin has been identified as a major information gap in many ongoing projects, such as the establishment of minimum flows and minimum water levels (MFL) criteria and the CRE Water Reservation projects. Unfortunately, there is no adequate flow monitoring network in the Tidal Caloosahatchee Subwatershed[6] to provide long-term freshwater inflow information. Developing a watershed hydrologic model is the best option to generate long-term surface runoff and groundwater inflows. This information will greatly help operate the main control point located at the S-79 structure located at the head of the CRE, other upstream flow control structures (S-77 and S-78), and retention ponds/reservoirs to achieve the best CRE coastal ecologic management.

This project developed a watershed hydrologic model named the WaSh Model for the Tidal Caloosahatchee Subwatershed to meet the aforementioned need. South Florida has unique hydrologic features, such as high water table, significant infiltration due to gentle elevation gradients, high soil hydraulic conductivity, and tidal effect. The WaSh model was designed to accommodate these hydrologic features. In this study, the hydrologic module of WaSh was further modified to better reflect groundwater quick response to infiltration. This module is the Hydrologic Simulation Program – Fortran (HSPF) for pervious areas (PWATER). The modification leads to significant improvement of groundwater simulation. A semi-implicit scheme is employed to quantify the water exchange between surface water and groundwater. The model was calibrated and validated with atmospheric and hydrologic data from 2008 to 2012. The simulated flow and groundwater stage show good agreement with the measured data. The model performance was assessed by bias, root mean square error (RMSE), coefficient of determination (R^2), and Nash-Sutcliffe Efficiency (NSE). Long-term (1967 to 2012) surface runoff and groundwater seepage were generated using the developed model. The simulation results show that the freshwater inflow from the Tidal Caloosahatchee Subwatershed is about 20% of total inflow to the estuary (80% from S-79, which includes inflow from the C-43 Watershed and Lake Okeechobee). The groundwater variation through wet to dry season was analyzed with the model along the CRE main channel. The freshwater inflows to the CRE generated by the WaSh Model could be used for many other projects such as water reservation development and salinity management.

[6] The Tidal Caloosahatchee Subwatershed is referred to as the Tidal Basin within the *Assessment of the Responses of the Caloosahatchee River Estuary to Low Freshwater Inflow in the Dry Season* document (Buzzelli et al. 2017) as well as other documents including the South Florida Environmental Reports.

INTRODUCTION

Estuaries are described as places where fresh water from rivers mix with salt water from the sea. Freshwater inflow to an estuary is critical for the estuary ecosystem management, such as salinity maintenance for ecosystem habitat. In the past decade, MFLs were developed for the Florida estuaries, which aimed at avoiding significant harm to the estuary ecosystems due to too little freshwater inflow from upstream watersheds (e.g. SFWMD 2000, 2002). The CRE is identified as an MFL waterbody that is afforded protection from significant harm to the ecosystem. The CRE receives freshwater inflows from the Tidal Caloosahatchee Subwatershed and the released flows from the S-79 structure.

The first effort to develop the MFL for the CRE was in 2000–2001 (SFWMD 2000), in which the output of a one-dimensional salinity model (Bierman 1993, 1997) was used to develop a regression equation to predict salinity values and correlating distance from the mouth of the CRE (Shell Point). This minimum flow criterion was based on the mean monthly flow at S-79 (SFWMD 2000, Doering et al. 2002). Due to the lack of flow information from the Tidal Caloosahatchee Subwatershed, both the one-dimensional salinity model and the regression equation did not reflect the impact of the subwatershed's freshwater inflow to salinity in the estuary (Edwards et al. 2000). It was strongly recommended that a mass-balance modeling approach be used in predicting salinity and assessing minimum flow in the CRE, instead of the empirical, statistical-regression black-box modeling approach (Edwards et al. 2000). Thus, the MFL for the CRE was reevaluated in 2003 using the Curvilinear Hydrodynamic Three-dimensional Model (CH3D) to develop a hydrodynamic and salinity model (SFWMD 2003). As indicated in Appendix A of SFWMD (2003), the developed CH3D hydrodynamic and salinity model still did not include adequate freshwater inflow from the CRE Tidal Caloosahatchee Subwatershed. The CH3D model requires further calibration using groundwater discharge and inflow from the Tidal Caloosahatchee Subwatershed. The freshwater inflow from Tidal Caloosahatchee Subwatershed becomes extremely important to the salinity and water quality in CRE during the dry season (November–April). Other ongoing projects, such as the CRE Water Reservation Project, are facing the same information gap for the CRE Tidal Caloosahatchee Subwatershed (Wan et al. 2010).

This project was to develop a distributed hydrologic watershed model using WaSh, which was successfully used for long-term simulation of watershed hydrology for the St. Lucie Estuary Watershed, Florida (URS, Inc. 2003, 2008b). Since November 2007, the Florida Department of Environmental Protection (FDEP), United States Geological Survey (USGS), and South Florida Water Management District (SFWMD or District) have been jointly working together on monitoring flows of the Tidal Caloosahatchee Subwatershed major tributaries. The period of record for measured flow data is short (2008–2012), however these measured flow and stage data make preliminary hydrologic watershed model development possible. The model was calibrated and verified using flow data at eight flow gage stations and five groundwater stage stations from 2008 to 2012. The model calibration and verification results are encouraging in terms of four model performance statistics, which are bias, RMSE, R^2, and NSE. The developed model was applied to simulate long-term (1967–2012) groundwater discharge and surface runoff from the Tidal Caloosahatchee Subwatershed to the CRE. The inflow time series, both groundwater and surface water from 1967 to 2005, were used as input to the CH3D.

STUDY AREA

The CRE, its tributaries, and associated basin are located on the lower west coast of Florida (**Figure D-1**). The historic Caloosahatchee River (now called the C-43 Canal) runs 43.5 miles (mi) (70 kilometers [km]) from Lake Okeechobee at Moore Haven (controlled by structures S-77 and S-78) to the Franklin Lock and Dam (S-79) at Olga. This part of the drainage area between S-77 and S-79 is called the C-43 Watershed. The S-79 structure acts as a salinity barrier by preventing salt water from traversing upstream into the C-43 Watershed. From the S-79 structure, the CRE extends 26.1 mi (42 km) downstream to Shell Point, where it empties into San Carlos Bay in the southern portion of the greater Charlotte Harbor System. The waterbody located downstream of the S-79 structure is called the CRE while the portion of the waterbody upstream of S-79 is called the C-43 Canal. The Tidal Caloosahatchee Subwatershed refers to the area draining to the CRE located between S-79 and Shell Point (**Figure D-1**).

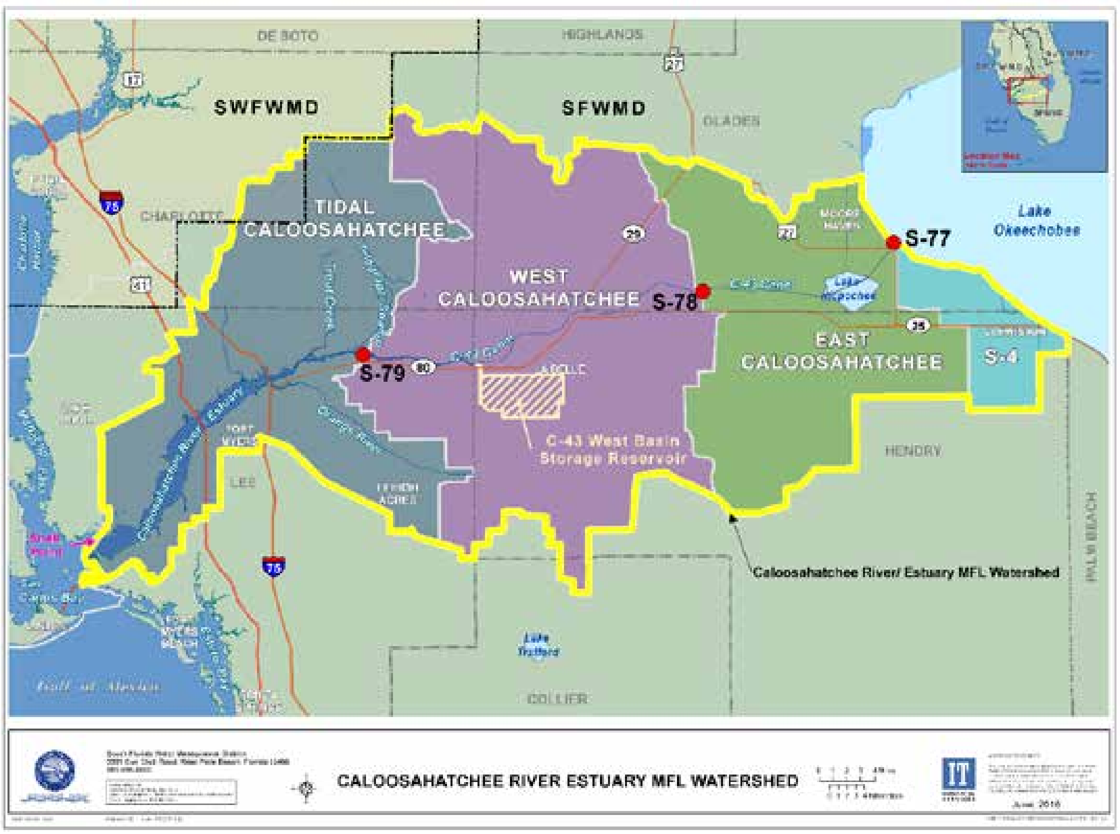

Figure D-1. CRE MFL Watershed.

The Tidal Caloosahatchee Subwatershed has a total of 264,705.50 acres and consists of eight subbasins (**Figure D-2**), which make up approximately 30% of the entire CRE MFL Watershed. Acres and area percentages for each subbasin of the Tidal Caloosahatchee Subwatershed are listed in **Table D-1**. The major subbasins in terms of area are the Orange River Subbasin (20.7%), Telegraph Creek Subbasin (20.3%), and Daughtrey Creek Subbasin (19.3%), which together total around 60% of the subwatershed area.

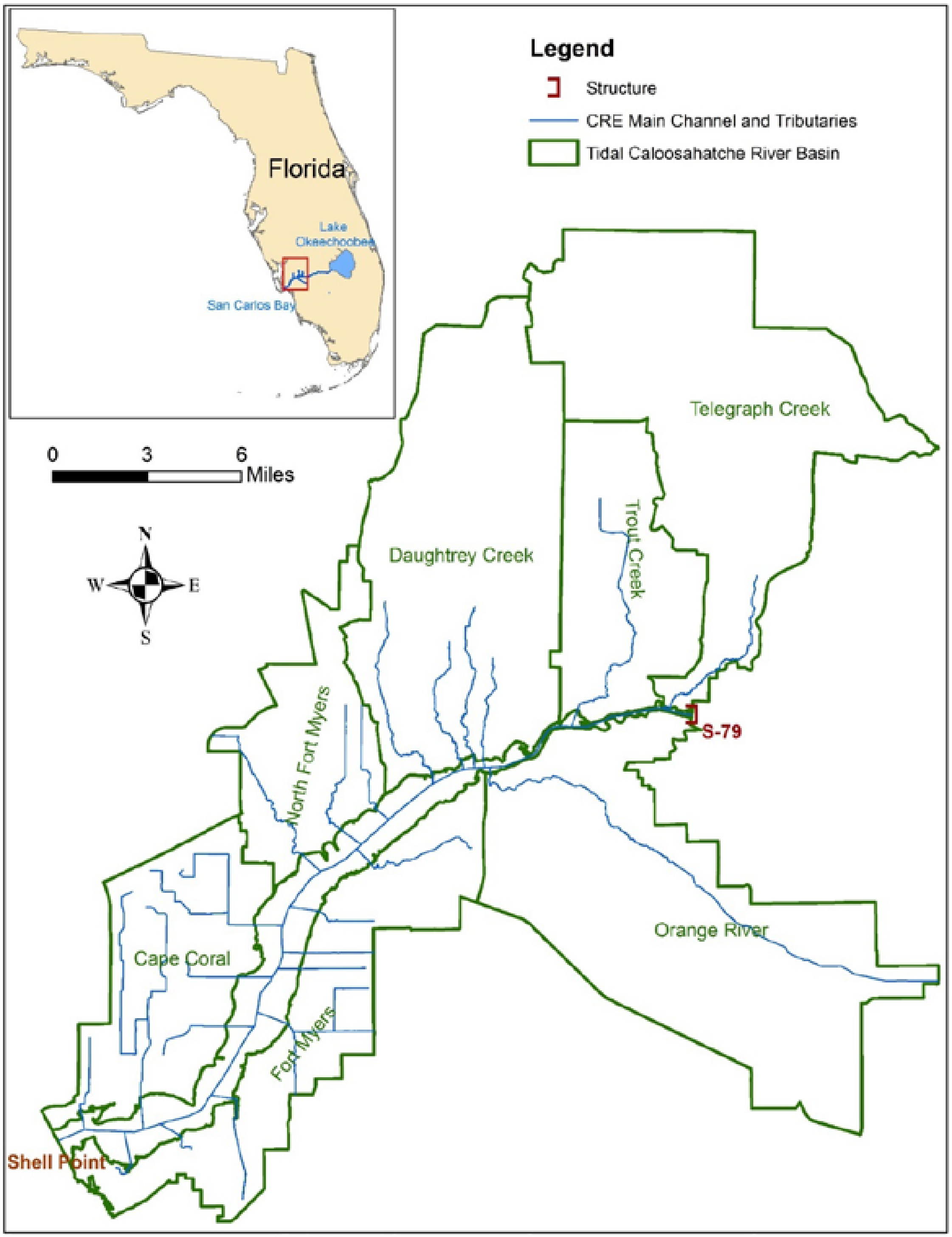

Figure D-2. Study Domain: Tidal Caloosahatchee Subwatershed.
(Note: The Tidal Caloosahatchee Subwatershed is referred to as Tidal Caloosahatchee River Basin on the map.)

Table D-1. Tidal Caloosahatchee Subwatershed tributary subbasins area distribution.

Subbasin Name	Area (acres)	Area (%)
Cape Coral	20,716.9	7.8
Fort Myers	27,209.2	10.3
Orange River	54,779.8	20.7
Caloosahatchee River Estuary	17,201.6	6.5
North Fort Myers	17,955.7	6.8
Trout Creek	22,019.5	8.3
Daughtrey Creek	51,017.9	19.3
Telegraph Creek	53,806.1	20.3
Total	**264,705.5**	**100**

HYDROLOGIC FEATURES

Clearly identifying key hydrologic features is crucial to conduct accurate hydrologic simulation for a watershed. The area of South Florida, extending from the Kissimmee River Basin (north of Lake Okeechobee) to Florida Bay, has its own unique hydrologic features shared by the Tidal Caloosahatchee Subwatershed as part of South Florida. This area has a very flat topographic terrain, with a dense drainage canal network, a subtropical rainy climate, and sandy soil in both the surficial unsaturated zone and surficial aquifer, subsequently creating a unique hydrologic system. The hydrologic characteristics of the Tidal Caloosahatchee Subwatershed and South Florida are summarized below.

Low Gradient Drainage with Sandy Soils

The Tidal Caloosahatchee Subwatershed has extremely low (-1.23 to 67.56 feet [ft] North American Vertical Datum of 1988 [NAVD88]) and flat topographic terrain with a slope of less than 22 inches per mi (35 centimeters [cm]/km) on average. This flat terrain restricts the velocity of overland flow reducing the total quantity of runoff by allowing more time for infiltration. Sandy soils with high permeability allow for a high infiltration and percolation of rainfall into the subsurface water. Horizontal sheet flow usually only occurs when the groundwater table rises above the ground surface. The flat terrain with abundant rainfall results in a prevalence of wetlands and ponds that have long-term surface inundation except where it is prevented by drainage systems.

High Groundwater Table

Flat terrain along with sandy soil resulting in substantial infiltration causes the groundwater table to rise quickly and sometimes above the ground surface when heavy rainfall occurs. High groundwater table in sandy soil with high hydraulic conductivity leads to remarkable groundwater flow discharge to a canal, and, consequently, the groundwater table may drop down quickly. Thus, the significant fluctuation in the groundwater table is typically observed. The interaction between the groundwater table at the surficial aquifer and unsaturated zone becomes a key hydrologic process.

Extensive Drainage Canal Network

Due to the combination of topographic low relief feature and tide effect (e.g. high tide lessens drainage capacity), the surface water drainage relies heavily on man-made canal networks with flow control structures, such as pump stations and gated spillways, to avoid flooding, especially in coastal and agriculture areas. Three-tier (tertiary, secondary, and primary) canal networks have been intensively constructed over several decades, particularly in urban and agriculture areas. This adds to the complexity of the surface flow hydraulics and hydrologic connections, where flows are not solely a function of local surface gradient and roughness. This also implies that a two-dimensional sheet flow routing method may not be applicable.

MODEL DESCRIPTION

The WaSh Model is a coupled watershed hydrologic model developed through a joint effort between URS, Inc. (now AECOM) and SFWMD. The model simulates both watershed quantity and quality (URS, Inc. 2008c). The WaSh Model was originally developed to simulate watershed hydrology and water quality for the St. Lucie Estuary Watershed, which shares the same unique hydrologic features in South Florida involving dense drainage canal systems, high water tables, and multiple irrigation sources. Due to these similarities in hydrology, the WaSh Model was selected and developed to simulate Tidal Caloosahatchee Subwatershed watershed hydrology in the reevaluation of the CRE MFL Rule. The model has a cell-based representation of the watershed surface where hydrology is modeled with the HSPF hydrology module PWATER for pervious areas and IWATER for impervious areas. The infiltrated water is routed to a diffusive wave groundwater model that represents the water table aquifer of simulated watersheds. The surface runoff is routed to a fully dynamic wave drainage network model that has the capacity to simulate bidirectional flow, branches, and common flow structures. An ArcGIS graphical user interface (GUI) has been developed to facilitate model configuration, including key watershed management strategies in South Florida such as implementation of best management practices, land use changes, and operations of reservoirs or stormwater treatment areas (STAs).

The theory and data requirements for hydrological simulation with the WaSh Mode, including water quantity and water quality, are described in URS, Inc. (2008c). URS, Inc. (2008d) is the model user’s manual providing a detailed reference for each function and feature of the WaSh Model along with URS, Inc. (2008a), which contains a tutorial that demonstrates various aspects of the WaSh Model application.

Hydrology Module

The surface water hydrology in WaSh is simulated using PWATER and IWATER modules of the USGS HSPF Version 12. The HSPF is a set of computer codes that can simulate the hydrologic and associated water quality processes on pervious and impervious land surfaces, in the soil profile, and in streams and well-mixed impoundments (Barnwell and Johanson 1981, Bicknell et al. 1997). The algorithms involved in PWATER are based on the Stanford Watershed Model IV (Crawford and Linsley 1966). The PWATER routine simulates rainfall, evaporation and evapotranspiration (ET), infiltration, percolation, and surface runoff. HSPF Version 12 includes recent model enhancements that simulate irrigation demand (AQUA TERRA 1998) and high water table conditions (AQUA TERRA 1996). The PWATER algorithms are summarized in **Attachment D-1** of this appendix.

It was found that the PWATER module was not able to properly simulate the high water table impact on unsaturated zone hydrology in this modeling application. The simulated groundwater table did not have adequate response to infiltration compared with the measured data. The whole PWATER source code was reviewed and the percolation from upper zone and lower zone were modified in this study. With this modification, the simulated groundwater table was significantly improved. The modification is presented in the *Modification to Lower Zone Inflow to Improve Groundwater Response* section of **Attachment D-1** and the improvement of groundwater simulation is presented in **Attachment D-4**.

A study domain is discretized into grid cells for model application. PWATER and IWATER modules are applied to each cell to simulate hydrologic processes. The results from the hydrologic module include ET, infiltration, soil water storage, percolation to groundwater, and surface runoff.

Surface Runoff Routing

A special cell attribute has been developed to identify both cell discharge routing and groundwater exchanges with other objects (i.e. tertiary canals, reservoirs, reaches) in the model. Each cell is labeled as one of six types:

- **No Feature Cell –** Cell without canal, reservoir, or reach
- **Canal Cell –** Cell contains canal but no reservoir or reach
- **Reach Cell –** Cell contains reach but no canal and reservoir
- **Canal-Reach Cell –** Cell contains canal and reach but no reservoir
- **Reservoir Cell –** Cell contains reservoir but no canal and reach
- **Canal-Reservoir Cell –** Cell contains canal and reservoir but no reach

A no feature cell does not contain tertiary canals, reservoirs or reach segment, its surface runoff is routed to an adjacent cells based on the local land slope. If a cell’s runoff is routed to an adjacent cell that does not have tertiary canals, then the runoff is added to the adjacent cell’s surface water storage. In a canal cell, the cell’s surface runoff is routed to the cell’s tertiary canals, and then is routed from the tertiary canals to a reach or reservoir of the nearest cell. Except for a no feature cell, a cell’s groundwater will interact with water in a reach, a reservoir, or a canal based on Darcy’s Law. The routing direction of surface runoff from cell to cell is based on the topographic gradients and knowledge of local hydrologic connections. Cell surface runoff resulting from PWATER and IWATER are sent to a tertiary canal directly. For inflow from a tertiary canal to a reach or reservoir, there are two options: weir-controlled flow or pump flow. The weir elevation/coefficient and pump rate are model parameters and need to be calibrated.

Stream Flow Simulation

The reach network flow routing is simulated by one-dimensional shallow water dynamic wave equations:

- Continuity equation

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = Q_{io} \qquad \boldsymbol{D.1}$$

- Momentum equation

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g\frac{\partial y}{\partial x} - g\left(S_0 - S_f\right) = 0 \qquad \boldsymbol{D.2}$$

where[7]

Q = flow rate (L^3/T)
A = cross section flow area (L^2)
y = water depth (L)
S_0 = reach bottom slope (L/L)
S_f = friction slope
g = gravitational acceleration (L/T^2)
x = axis along the reach direction (L)
t = time (T)
Q_{io} = lateral inflow and outflow ($L^3/T/L$)

Please note that lateral inflow and outflow (Q_{io}) includes local cell surface runoff inflow, net flux due to rainfall and evaporation, external source flow sources to the reach, and water exchange between reach and canal, between reservoir and reach, and between aquifer groundwater and reach.

From Manning's equation shown below:

$$v = \frac{1.49}{n} R^{\frac{2}{3}} S_f^{\frac{1}{2}} \qquad \boldsymbol{D.3}$$

We obtained the following:

$$S_f = \left(\frac{n}{1.49}\right)^2 \frac{1}{R^{\frac{4}{3}}} v|v| \qquad \boldsymbol{D.4}$$

where

v = flow velocity (L/T)
n = Manning's roughness
R = hydraulic radius (L)
S_f = friction slope (L/L)

[7] L – length and T – time.

In coastal areas, the convective acceleration term is small and negligible. Thus, the momentum equation (**D.2**) becomes the following:

$$\frac{1}{A}\frac{\partial Q}{\partial t} + g\frac{\partial y}{\partial x} - g\left(S_0 - S_f\right) = 0 \qquad \boldsymbol{D.5}$$

Using water surface elevation in the equation, we have the following:

$$\frac{1}{A}\frac{\partial Q}{\partial t} + g\frac{\partial h}{\partial x} + gS_f = 0 \qquad \boldsymbol{D.6}$$

where

$h = y + z$

$S_0 = -\frac{\partial z}{\partial x}$

$z = \text{reach bottom elevation}$

Then, the equation (**D.6**) can be further rearranged as follows:

$$\frac{\partial Q}{\partial t} = -gA\frac{\partial h}{\partial x} - gAS_f \qquad \boldsymbol{D.7}$$

When reach is discretized into a series of nodes and segments (**Figure D-3**), the explicit finite difference scheme for node k from rectangular reach segment $k - 1/2$ to segment $k + 1/2$ with width of w ($A = wy$) (assuming rectangular cross-section) is as follows:

$$\frac{Q_k^{t+1} - Q_k^t}{\Delta t} = -gA\frac{h_{k+\frac{1}{2}}^t - h_{k-\frac{1}{2}}^t}{\Delta x} - gA\left(\frac{n}{1.49}\right)^2\frac{1}{R^{\frac{4}{3}}}v|v|$$

$$= -gwy\frac{h_{k+\frac{1}{2}}^t - h_{k-\frac{1}{2}}^t}{\Delta x} - gwy\left(\frac{n}{1.49}\right)^2\frac{1}{R^{\frac{4}{3}}}v|v| \qquad \boldsymbol{D.8}$$

where

$\Delta t = \text{time step}$

$\Delta x = \text{space step, i.e. length of segment}$

Thus, the flow through node k from segment $k - \frac{1}{2}$ to segment $k + \frac{1}{2}$ is as follows:

$$Q_k^{t+1} = Q_k^t + g\left(\frac{w_{k-\frac{1}{2}}^t + w_{k+\frac{1}{2}}^t}{2}\right)\left(\frac{y_{k-\frac{1}{2}}^t + y_{k+\frac{1}{2}}^t}{2}\right)\left(\frac{y_{k-\frac{1}{2}}^t - y_{k+\frac{1}{2}}^t}{\Delta x} + \frac{z_{k-\frac{1}{2}}^t - z_{k+\frac{1}{2}}^t}{\Delta x}\right)\Delta t$$

$$- g\left(\frac{w_{k-\frac{1}{2}}^t + w_{k+\frac{1}{2}}^t}{2}\right)\left(\frac{y_{k-\frac{1}{2}}^t + y_{k+\frac{1}{2}}^t}{2}\right)\left(\frac{n}{1.49}\right)^2\left(\frac{v_k^t|v_k^t|}{R^{\frac{4}{3}}}\right)\Delta t \qquad \boldsymbol{D.9}$$

When the reach cross-section is rectangular, the continuity equation (**D.1**) becomes **Equation D.10**:

$$\frac{\partial(wh)}{\partial t} + \frac{\partial Q}{\partial x} = Q_{io} \qquad \boldsymbol{D.10}$$

The explicit finite difference scheme of the **Equation D.10** for segment $k + 1/2$ is as follows:

$$\frac{w_{k+\frac{1}{2}}(y_{k+\frac{1}{2}}^{t+1} - y_{k+\frac{1}{2}}^{t})}{\Delta t} + \frac{Q_{k+1}^{t+1} - Q_{k}^{t+1}}{\Delta x} = Q_{io}{}_{k+\frac{1}{2}}^{t+1} \qquad \boldsymbol{D.11}$$

With some further rearrangement, we have **Equation D.12**:

$$y_{k+\frac{1}{2}}^{t+1} = y_{k+\frac{1}{2}}^{t} + \left(Q_{io}{}_{k+\frac{1}{2}}^{t+1} - \frac{Q_{k+1}^{t+1} - Q_{k}^{t+1}}{\Delta x}\right)\frac{\Delta t}{w_{k+\frac{1}{2}}} \qquad \boldsymbol{D.12}$$

Equations D.9 and **D.11** are the final formulae used to route reach flow in the WaSh Model.

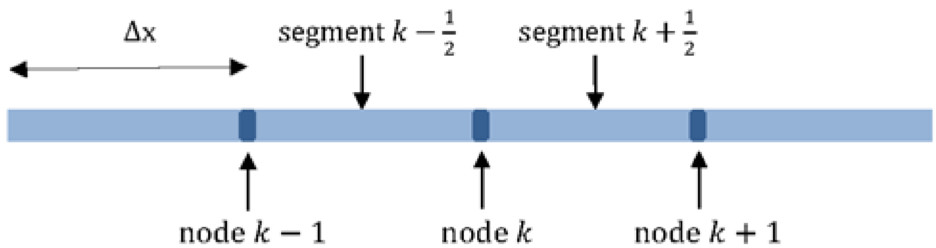

Figure D-3. Segments and nodes of discretized reach.

Groundwater Flow Simulation

The groundwater module is based on the numerical solution to the standard groundwater flow Boussinesq Equation (Darcy's Law and Continuity) for an unconfined aquifer with Dupuit assumptions (Anderson and Woessner 2002, URS, Inc. 2008c):

$$n\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(K_x(h - h_c)\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y(h - h_c)\frac{\partial h}{\partial y}\right) + S_i - S_o + Q_{c-gw} + Q_{r-gw} + Q_{res-gw} \qquad \boldsymbol{D.13}$$

where

h = groundwater table elevation relative to model datum (for instance, National Geodetic Vertical Datum of 1929 [NGVD29]) (L)

t = time (T)

x and y = spatial coordinates in horizontal domain (L)

n = the specific yield

K_x and K_y = hydraulic conductivity x and y directions (L/T)

h_c = elevation of aquifer base relative to model datum (L)

S_i = source term ($L^3/T/L^2$)

S_o = sink term ($L^3/T/L^2$)

Q_{c-gw} = wate exchange between canal and aquifer ($L^3/T/L^2$)

Q_{r-gw} = wate exchange between reach and aquifer ($L^3/T/L^2$)

Q_{res-gw} = wate exchange between reservoir and aquifer ($L^3/T/L^2$)

Two of the source (or sink) terms on the right-hand side of the equation, S_i and S_o, are deep percolation and evaporation respectively, which are outputs from the WaSh hydrology module (specifically, the WaSh implementation of the HSPF PWATER/IWATER module). The deep percolation is set to the HSPF output PERC:

$$S_i = PERC \qquad \textbf{D.14}$$

The evaporation is set equal to the original HSPF groundwater evaporation rate AGWET:

$$S_o = AGWET \qquad \textbf{D.15}$$

The detail of methods for calculating percolation and groundwater evaporation can be found in the HSPF documentation (Bicknell et al. 1997).

The governing equation is solved numerically using the basin grid cell structure. A second-order finite difference approximation is used for the second derivatives, and an explicit forward difference approximation is used for the time derivative. By designating the equation parameters and water elevation h for each cell by the indexes i and j, and the time level by the index t, the resulting finite difference equation for each cell is as follows:

$$\begin{aligned}
n_{i,j}\frac{h_{i,j}^{t+1}-h_{i,j}^{t}}{\Delta t} = {} & \left[\left(\frac{2}{\frac{1}{K_{x_{i+1,j}}}+\frac{1}{K_{x_{i,j}}}}\right)\frac{\left(\frac{h_{i+1,j}^{t}+h_{i,j}^{t}}{2}-\frac{h_{c_{i+1,j}}^{t}+h_{c_{i,j}}^{t}}{2}\right)}{\Delta x}\left(\frac{h_{i+1,j}^{t}-h_{i,j}^{t}}{\Delta x}\right)\right. \\
& \left. -\left(\frac{2}{\frac{1}{K_{x_{i,j}}}+\frac{1}{K_{x_{i-1,j}}}}\right)\frac{\left(\frac{h_{i,j}^{t}+h_{i-1,j}^{t}}{2}-\frac{h_{c_{i,j}}^{t}+h_{c_{i-1,j}}^{t}}{2}\right)}{\Delta x}\left(\frac{h_{i,j}^{t}-h_{i-1,j}^{t}}{\Delta x}\right)\right] \\
& +\left[\left(\frac{2}{\frac{1}{K_{x_{i,j+1}}}+\frac{1}{K_{x_{i,j}}}}\right)\frac{\left(\frac{h_{i,j}^{t}+h_{i,j+1}^{t}}{2}-\frac{h_{c_{i,j}}^{t}+h_{c_{i,j+1}}^{t}}{2}\right)}{\Delta y}\left(\frac{h_{i,j+1}^{t}-h_{i,j}^{t}}{\Delta y}\right)\right. \\
& \left. -\left(\frac{2}{\frac{1}{K_{x_{i,j}}}+\frac{1}{K_{x_{i,j-1}}}}\right)\frac{\left(\frac{h_{i,j}^{t}+h_{i,j-1}^{t}}{2}-\frac{h_{c_{i,j}}^{t}+h_{c_{i,j-1}}^{t}}{2}\right)}{\Delta y}\left(\frac{h_{i,j}^{t}-h_{i,j-1}^{t}}{\Delta y}\right)\right]+S_{i_{i,j}}^{t} \\
& -S_{o_{i,j}}^{t}+Q_{c-gw_{i,j}}^{t}+Q_{r-gw_{i,j}}^{t} \\
& +Q_{res-gw_{i,j}}^{t} \qquad \textbf{D.16}
\end{aligned}$$

where

Δt = time step (T)

Δx and Δy = grid cell dimensions in x and y direction (L)

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 $h_{i,j}^{t+1}$.

Water Exchanges between Model Objects

The routing schemes for each individual component described in previous sections for groundwater, tertiary canals, reaches, and reservoirs contains numerous interactions between components. The computations of these interactions are addressed below.

Between Canal and Groundwater

When a cell has tertiary canal, the canal will exchange water with the groundwater in the cell according to a conductance-based formulation:

$$Q_{c-gw} = \left(h_{gw} - h_{tc}\right)C_{tc} \qquad \boldsymbol{D.17}$$

where

h_{gw} = groundwater table elevation (L)

h_{tc} = tertiary canal water stage elevation (L)

C_{tc} = tertiary canal bed conductance (L^2/T)

The discharge can be positive or negative depending on the relative elevations of the groundwater and tertiary canal surface water. The tertiary canal bed conductance is defined as follows:

$$C_{tc} = \frac{L_c P_c K_{c-gw}}{d_c} \qquad \boldsymbol{D.18}$$

where

L_c = canal length (L)

P_c = wetted perimeter of canal cross section (L)

d_c = thickness of canal bed materical (L)

K_{c-gw} = hydraulic conductivity of canal bed material (L/T)

Between Reach and Groundwater

When a cell intersects a reach in the reach network, the reach will exchange water with the cell's groundwater according to a conductance-based formulation:

$$Q_{r-gw} = \left(h_{gw} - h_r\right)C_r \qquad \boldsymbol{D.19}$$

where

h_r = surface water stage eleveation in reach (L)

C_r = reach bed conductance (L^2/T)

The reach bed conductance is defined as follows:

$$C_r = \frac{L_r P_r K_{r-gw}}{d_r} \qquad \boldsymbol{D.20}$$

where

L_r = reach length (L)

P_r = wetted perimeter of reach cross section (L)

d_r = thickness of reach bed material (L)

K_{r-gw} = hydraulic conductivity of reach bed material (L^2/T)

Between Reservoir and Groundwater

The cells intersecting the reservoir are those that have had their cell area reduced due to the reservoir footprint overlying the cell. Cells that are completely covered by the reservoir are removed from the model and are not considered for groundwater exchanges.

When a cell intersects a reservoir, the reservoir will exchange water with the cell's groundwater according to the following:

$$Q_{res-gw} = \frac{\left(0.5\left(h_{gw} + h_{res}\right) - h_{base}\right)\left(h_{gw} - h_{res}\right)K_{res-gw}\sqrt{A_{res}}}{\sqrt{A_{cell}}} \qquad \boldsymbol{D}.\mathbf{21}$$

where

h_{res} = reservoir surface water stage elevation (L)

h_{gw} = groundwater table evelation in the cell (L)

h_{base} = surficial aquifer bottom elevation (L)

A_{res} = reservoir/STA water surface area (L^2)

A_{cell} = cell area (L^2)

K_{res-gw} = hydraulic conductivity of reach bed material (L^2/T)

Between Tertiary Canal and Reach

For each cell with tertiary canals, there are two options for controlling the discharge from the tertiary canal to the designated reach, either weir-controlled flow or pump flow. For weir-controlled flow the equation is as follows:

$$Q_{c-r} = \begin{cases} C_{c-r}W_{c-r}(h_{tc} - h_{weir})^{1.5} & if \quad h_{tc} > h_{weir} \\ 0 & if \quad h_{tc} \le h_{weir} \end{cases} \qquad \boldsymbol{D}.\mathbf{22}$$

where

C_{c-r} = weir coefficient

W_{c-r} = weir width (L)

h_{weir} = weir crest elevation (L)

For the pumping option, the tertiary canals are pumped at the pumping rate P_{tc} when the water elevation rises above a prescribed level H_{tc}^{max}, and then pumping continues until the water level in the tertiary canals drops below another prescribed level, H_{tc}^{cutoff}. This approach allows for simulation of "pumping down" the tertiary canals, a practice used in many agricultural and urban areas during the wet season. The pump discharge is sent to the designated reach.

Also, for agricultural irrigation purpose, the tertiary canal pumps can be used to pump from the reach to the tertiary canals. This option is used when an irrigation demand exists for a cell, and the supply form the tertiary canal is exhausted because the tertiary canals become dry.

Between Tertiary Canal and Reservoir

For each cell with tertiary canal, there are two options for controlling the discharge from the tertiary canal to the designated reservoir: weir-controlled flow or pumped flow. These options and the option for pumping from the reservoir to the tertiary canal to replenish irrigation water supply are essentially identical to those for the tertiary canal-reach exchange. For weir-controlled flow the equation is as follows:

$$Q_{c-res} = \begin{cases} C_{c-res} W_{c-res} (h_{tc} - h_{weir})^{1.5} \; if \quad h_{tc} > h_{weir} \\ 0 \qquad\qquad\qquad\qquad\qquad if \quad h_{tc} \le h_{weir} \end{cases} \qquad \boldsymbol{D}.\mathbf{23}$$

where

C_{c-r} = weir coefficient

W_{c-r} = weir width (L)

h_{weir} = weir crest elevation (L)

For the pumping option, the tertiary canals are pumped at the pumping rate P_{tc} when the water elevation rises above a prescribed level H_{tc}^{max}, and then pumping continues until the water level in the tertiary canals drops below another prescribed level, H_{tc}^{cutoff}. The pump discharge is sent to the designated reservoir.

Also, the tertiary canal pumps can be used to pump from the reservoir to the tertiary canals, this option is used when an irrigation demand exists for a cell, and the supply from the tertiary canal is exhausted because the tertiary become dry. When these conditions occur, the WaSh model will pump water from the reservoir at rate P_{tc} until the canals reach the H_{tc}^{cutoff} level.

Between Reach and Reservoir

The water exchange between reach and reservoir/STA are accomplished through four types of structures: culvert, weir, pump, and gated spillway (for computation formulae for each type of flow see URS [2008c]). Flow equations of the four types of structures were included for flow exchange computation. The operation rules for those structures can be specified by users. In addition, the four types of structures can be placed along a reach.

MODEL INPUT DATA

Topography

The digital topographic elevation for Tidal Caloosahatchee Subwatershed is shown in **Figure D-4**.

The northern part of Telegraph Creek has higher elevations (maximum elevation is 67.56 ft NGVD88) while south Fort Myers, Cape Coral, and the outlet part of CRE are lower elevations (minimum elevation is -1.23 ft NGVD88). Over the entire basin, the average slope is about 0.00035 ft/ft. Telegraph Creek subbasin has the largest slope, which is about 0.0008 ft/ft while

Fort Myers has the smallest slope, which is about 0.0001 ft/ft. The basin is fairly flat with little or no topographical relief. A large number of wetlands and retention ponds are, however, found scattered across the basin.

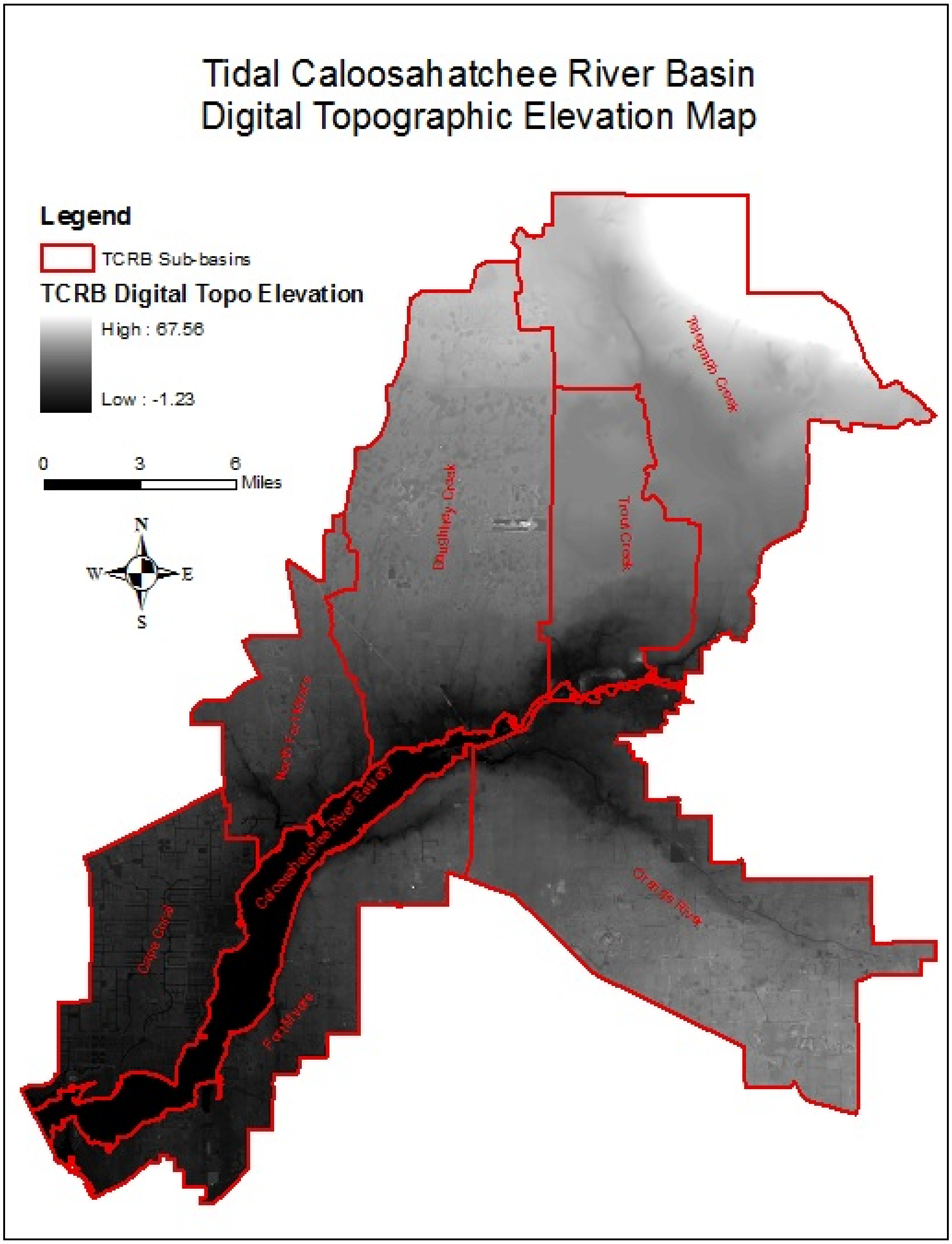

Figure D-4. Digital topographic elevation map for the Tidal Caloosahatchee Subwatershed. (Notes: Units are ft NAVD88. Resolution of 100 ft by 100 ft. The Tidal Caloosahatchee Subwatersehd is referred to as the Tidal Caloosahatchee River Basin [TCRB] on the map.)

Land Use

The 2008/2009 land use data for Tidal Caloosahatchee Subwatershed shown in **Figure D-5** was used for calibration and verification of the model. **Table D-2** contains the acres of each subbasin and **Table D-3** shows the percentage.

Overall, the Tidal Caloosahatchee Subwatershed has four major land use types, which are 95,044.4 acres (ac) in urban (35.9%), 42,093.3 ac in upland forest (15.9%), 39,174.7 ac in wetland (14.8%), and 38,838.0 ac in agriculture (14.7%). Rangeland has an area of 22,200.1 ac (8.4%), and water has 23,179.1 ac (8.8%). The rest of the land uses are transportation, communication, and utilities (3,721.8 ac, 1.4%), and barren land (455.3 ac, 0.2%). Each subbasin land use components are described in detail below.

The CRE has an area of 17,201.6 ac. Water is the major land use type (16,630.6 ac, 96.7%). Wetland is 423.3 ac (2.5%). Other land use types are about 1%.

The Cape Coral Subbasin has an area of 20,715.7 ac. Its major land type is urban (16,037.8 ac, 77.4%). Water is about 12.8% (2,660.9). Other land use types are less than 10%.

The Daughtrey Creek Subbasin has an area of 51,017.9 ac. Wetland and upland forest are the two major land use types, which are 12,764.2 ac (25.0%) and 11,304.3 ac (22.2%), respectively. The other three important land use types are urban (8,947.6 ac, 17.5%), rangeland (8,262.6 ac, 16.2%), and agriculture (8,690.1 ac, 17.0%). Water; barren land; and transportation, communication, and utilities are minor land use types (less than 2%).

The Fort Myers Subbasin has 27,209.2 ac. Urban is its major land use type (20,566.2 ac, 75.6%). The wetland is 2,122.9 ac (7.8%) and water is 1,413.5 ac (5.2%). The area of upland forest is 1,260.0 (4.6%), which is very close to transportation, communication, and utilities (1,254.3 ac, 4.6%). Agriculture area is about 1.2% (339.0 ac). Other land types (rangeland and barren land) are less than 1%.

The North Fort Myers Subbasin has 17,955.7 ac. Its major land use types are urban (9,561.5 ac, 53.3%) and upland forest (3,910.7 ac, 21.8%). Other land use types areas are wetland (1,455.4 ac, 8.1%); rangeland (1,328.0 ac, 7.4%); agriculture (650.0 ac, 3.6%); transportation, communication, and utilities (554.2 ac, 3.1%); and barren land (32.2 ac, 0.1%).

The Orange River Subbasin has an area of 54,779.8 ac. The major land use types in this subbasin are urban (38,430.3 ac, 70.2%), followed by wetland (4,357.1 ac, 8.0%), agriculture (4,300.4 ac, 7.9%), and upland forest (3,158.0, 5.8%). Rangeland has 1,755.3 ac (3.2%) and water makes up 1,460.0 ac (2.7%). The other land uses, which total less than 3% of the subbasin's area, are barren land and transportation, communication, and utilities.

The Telegraph Creek Subbasin has an area of 53,806.1 ac. The major land use types are upland forest, agriculture, and wetland, which are 16,961.7 ac (31.5%), 15,007.5 ac (27.9%), and 13,165.7 ac (24.5%), respectively. Rangeland has an area of 8,364.8 (15.5%) while other land use types are very minor (less than 1%).

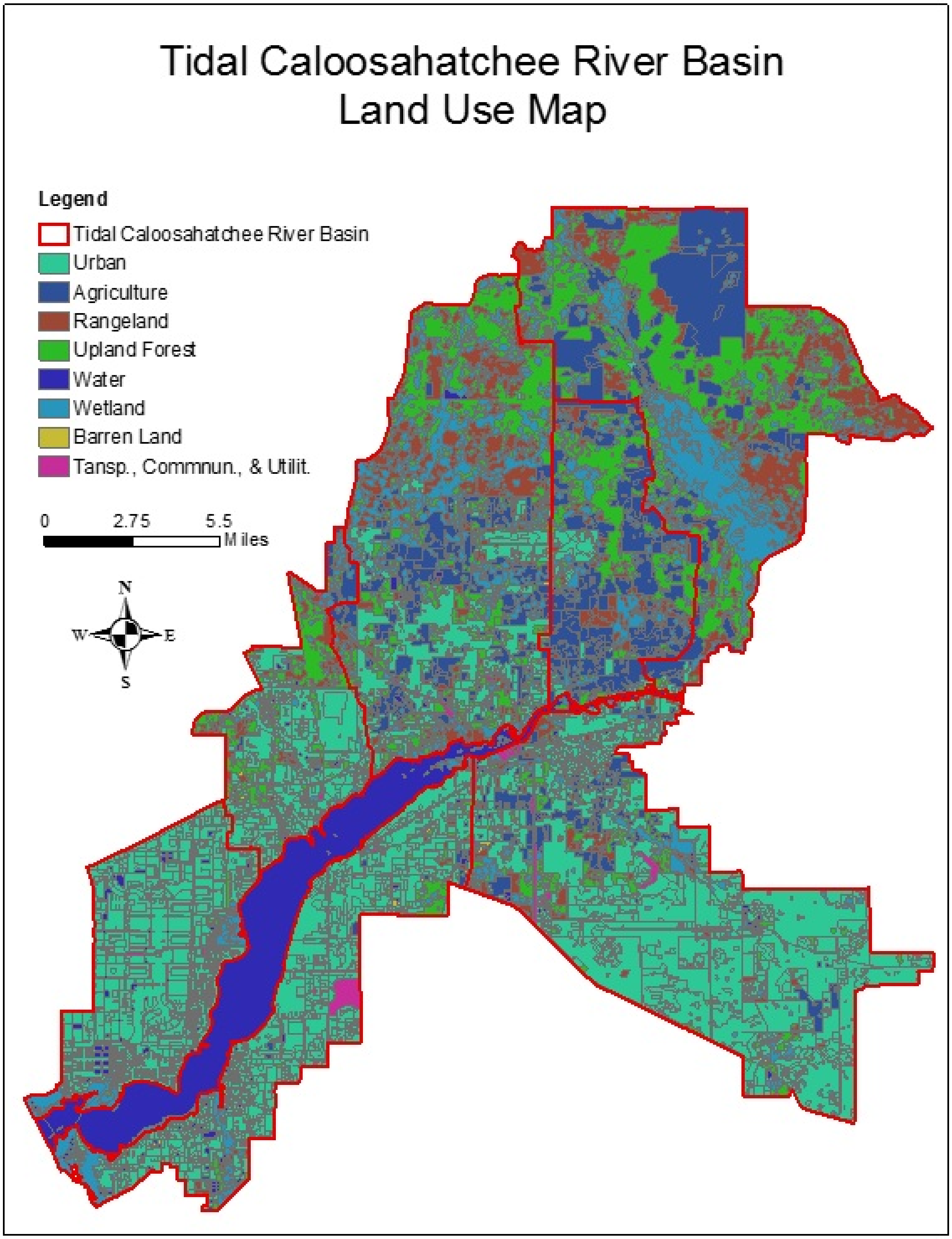

Figure D-5. Land use map for the Tidal Caloosahatchee Subwatershed. (Notes: Tansp., Commnun. & Utilit. – Transportation, Communication and Utilities. The Tidal Caloosahatchee Subwatershed is referred to as the Tidal Caloosahatchee River Basin on the map.)

Table D-2. Land use data in acres for each subbasin.

Subbasin	Urban	Agriculture	Rangeland	Upland Forest	Water	Wetland	Barren Land	Transportation, Communication, & Utilities	Total
Caloosahatchee River Estuary	52.5	0.0	49.7	44.5	16,630.6	423.3	0.0	0.9	17,201.6
Cape Coral	16,037.8	0.0	21.2	155.2	2,660.9	1,497.7	0.0	342.9	20,715.7
Daughtrey Creek	8,947.6	8,690.1	8,262.6	11,304.3	483.4	12,764.2	32.5	533.1	51,017.9
Fort Myers	20,566.2	339.0	198.0	1,260.0	1,413.5	2,122.9	55.3	1,254.3	27,209.2
North Fort Myers	9,561.5	650.0	1,328.0	3,910.7	463.6	1,455.4	32.2	554.2	17,955.7
Orange River	38,430.3	4,300.4	1,755.3	3,158.0	1,460.0	4,357.1	290.8	1,027.9	54,779.8
Telegraph Creek	277.5	15,007.5	8,364.8	16,961.7	21.9	13,165.7	0.0	7.0	53,806.1
Trout Creek	1,170.9	9,850.9	2,220.4	5,298.8	43.9	3,388.4	44.6	1.5	22,019.5
Total	**95,044.4**	**38,838.0**	**22,200.1**	**42,093.3**	**23,179.1**	**39,174.7**	**455.3**	**3,721.8**	**264,705.5**

Table D-3. Land use data in percent for subbasins.

Subbasin	Urban	Agriculture	Rangeland	Upland Forest	Water	Wetland	Barren Land	Transportation, Communication, & Utilities	Total
Caloosahatchee River Estuary	0.3%	0.0%	0.3%	0.3%	96.7%	2.5%	0.0%	0.0%	6.5%
Cape Coral	77.4%	0.0%	0.1%	0.7%	12.8%	7.2%	0.0%	1.7%	7.8%
Daughtrey Creek	17.5%	17.0%	16.2%	22.2%	0.9%	25.0%	0.1%	1.0%	19.3%
Fort Myers	75.6%	1.2%	0.7%	4.6%	5.2%	7.8%	0.2%	4.6%	10.3%
North Fort Myers	53.3%	3.6%	7.4%	21.8%	2.6%	8.1%	0.2%	3.1%	6.8%
Orange River	70.2%	7.9%	3.2%	5.8%	2.7%	8.0%	0.5%	1.9%	20.7%
Telegraph Creek	0.5%	27.9%	15.5%	31.5%	0.0%	24.5%	0.0%	0.0%	20.3%
Trout Creek	5.3%	44.7%	10.1%	24.1%	0.2%	15.4%	0.2%	0.0%	8.3%
Total	**37.1%**	**14.7%**	**8.4%**	**15.9%**	**8.8%**	**14.8%**	**0.2%**	**1.4%**	**100.0%**

The Trout Creek Subbasin has 22,019.5 ac. Agriculture is the major land use type (9,850.9 ac, 44.7%) in the subbasin. The other four important land use types are upland forest (5,298.8 ac, 24.1%), wetland (3,388.4 ac, 15.4%), rangeland (2,220.4 ac, 10.1%), and urban (1,170.9 ac (5.3%). Water; barren land; and transportation, communication, and utilities are very minor (less 1%).

Soil

Soils in the Tidal Caloosahatchee Subwatershed are generally coarse and sandy with a high infiltration capacity. According to the soil types map in Fernald and Purdum (1998), there are three types of soil in Tidal Caloosahatchee Subwatershed:

- **Soils of the Flatwoods –** It is located in the northeastern part of the Tidal Caloosahatchee Subwatershed, including Daughtrey Creek, and North Fort Myers, Telegraph Creek, and Trout Creek.
- **Soils of Recent Limestone Origin –** This soil type is located in southeastern part of Tidal Caloosahatchee Subwatershed, including the north part of Fort Myers and Orange River.
- **Miscellaneous Coastal Land Types –** This type of soil is located close to the coastal area, including Cape Coral and the south part of Fort Myers.

Soil types determinate unsaturated zone hydrology, such as infiltration rate, interflow generation, and field capacity. Digital soil type geographic information system (GIS) data were obtained through the SFWMD GIS data catalog. The data are found under the FDEP Soils Soil Survey Geographic Database (SSURGO) – SFWMD database, which is located at https://www.sfwmd.gov/science-data/gis.

Soil types classified in hydrologic soil group based on the GIS data is shown in **Figure D-6**. The detail description about hydrologic soil group can be found in Maidment (1993). **Table D-4** shows area of each type of soil type in Tidal Caloosahatchee Subwatershed. Hydrologic soil group A/D has largest area of 11,0194 ac, (41.1% of the Tidal Caloosahatchee Subwatershed), followed by hydrologic soil group C/D (70,700.1 ac 26.4%), B/D (37,619.2 ac, 14.0%), B (18,036.5 ac, 6.4%), A (3,217.3 ac, 1.2%), and D (2,996.5 ac, 1.1%). The Tidal Caloosahatchee Subwatershed has about 9.4% (25,104.4 ac) area covered by water. This area is assumed to directly link to groundwater and no unsaturated zone exists. Thus, no hydrologic soil type is assigned to this area.

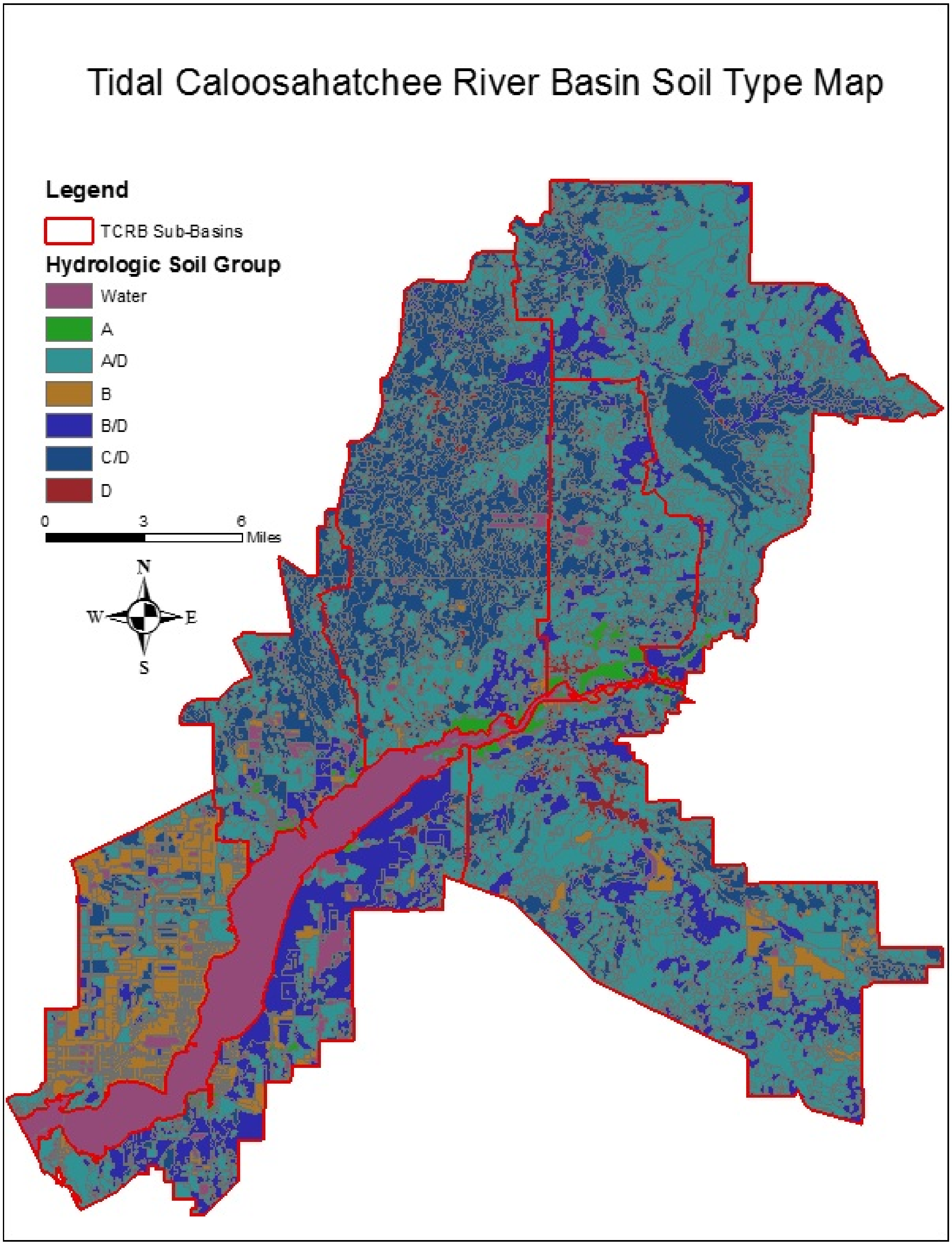

Figure D-6. Hydrologic soil group map for the Tidal Caloosahatchee Subwatershed. (Note: Tidal Caloosahatchee Subwatershed is referred to as the Tidal Caloosahatchee River Basin [TCRB] on the map.)

Table D-4. Hydrologic soil type area in the Tidal Caloosahatchee Subwatershed.

Hydrologic Soil Group	Area (ac)	Area (%)
A	3,217.3	1.2
A/D	110,194.4	41.6
B	18,036.5	6.8
B/D	34,456.3	13.0
C/D	70,700.1	26.7
D	2,996.5	1.1
Water	25,104.4	9.5
Total	**264,705.5**	**100**

Aquifer Hydrogeology

Groundwater flow through the surficial aquifer system (SAS) is simulated in the WaSh Model. Shallow water tables were found in most parts of the Tidal Caloosahatchee Subwatershed. The water table response to rainfall indicates a close link between rainfall, surface water, and groundwater (DHI Water & Environment 2002). The data required in the groundwater simulation module are thickness of surficial aquifer, porosity, and horizontal hydraulic conductivity.

Tidal Caloosahatchee Subwatershed is part of Florida Lower West Coast area. BEM System Inc. (2003) jointly with SFWMD and Earth*fx*, Inc. reviewed hydrostratigraphic surfaces of the Florida Lower West Coast SAS generated by Water Resources Solutions, Inc., and DHI Water & Environment, Inc., based on various data resources. These resources included, according to BEM Inc. and Earth*fx* Inc. (2003), the Water Resources Solutions, Inc., borehole database; the hydrogeologic borehole data within SFWMD's corporate environmental database, DBHYDRO; Florida Geological Survey borehole database, and a USGS report. Through the effort, hydrostratigraphic surfaces were developed to be more conducive to numerical modeling and the current definition is schematically shown in **Figure D-7**. The figure also shows a comparison of the historical and current definitions of the hydrostratigraphy of the SAS and part of the intermediate aquifer system (IAS).

In **Figure D-7**, the SAS consists of Layer 1 and Layer 2. Holocene to Pleistocene sands and late Pliocene (Pinecrest) limestone, where present, are considered equivalent to the unconfined aquifer (also known as water table aquifer), which is also defined as Aquifer Layer 1. Bonita Springs Marl and Caloosahatchee Clay, where present, form the confining unit (Aquitard Layer 1) that separates the water table aquifer from the Lower Tamiami aquifer below. Early Pliocene (Ochopee Limestone) constitutes Aquifer Layer 2. This unit conforms to the historical definition of Lower Tamiami aquifer, where confined, and to the lower part of the water table aquifer, where unconfined. The vertical extent of the unit is defined from top of the Ochopee Limestone to the top of the Upper Peace River Formation. Upper Peace River Clays is defined as Aquitard Layer 2.

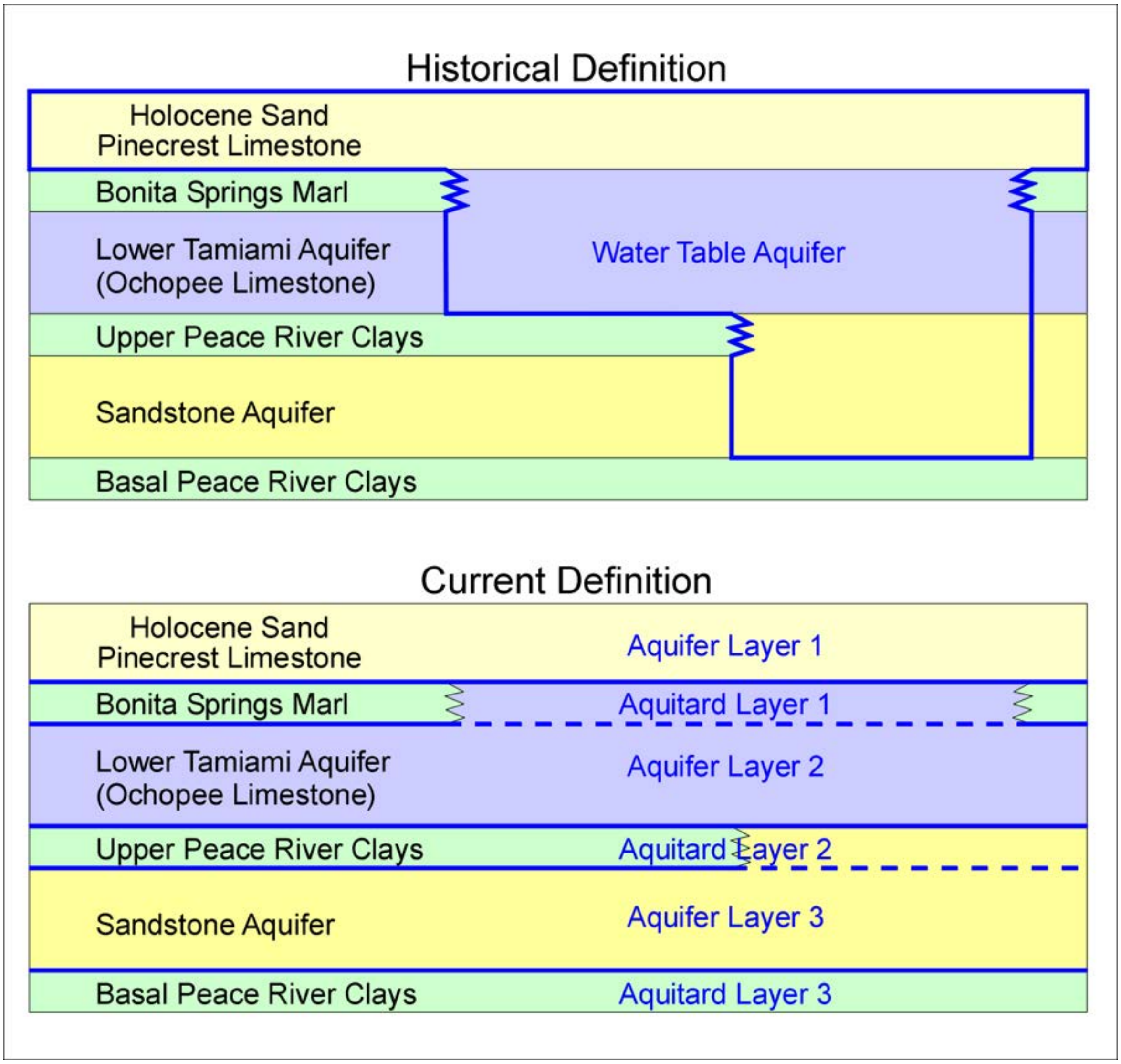

Figure D-7. Historic definition of aquifer and current definition of aquifer for modeling purposes for Florida Lower West Coast area. (Source: BEM System, Inc. 2003.)

The topmost aquifer of the IAS is the Sandstone aquifer, also called Aquifer Layer 3. This layer is defined as the layer between the Lehigh Acres Sandstone, which is the first sandstone unit in the Peace River Formation, to the top of the basal clay in the Peace River Formation. This layer includes all the sandstone units in the Peace River Formation and the interbedded clay units. The Aquitard Layer 3 at the base of the Sandstone aquifer is the Basal Peace River Clay, also called Fort Myers clay. Vertically, this unit extends to the top of the Arcadia Formation (not shown in the figure).

GIS coverage for the top elevations of each aquifer layer and aquitard layer and their thickness were generated by BEM System, Inc. (2003). These data were used in Lower West Coast Surficial Aquifer System Model development (Marco Water Engineering, Inc. and Ecology and Environment, Inc. 2006).

The water table aquifer is made up of primarily fine- to medium-grained quartz sands, with some clay and shell material of Pleistocene and Holocene Terrace deposits and sandy biogenic limestone deposits of the Tamiami Formation (Bennett 1992). The Lower Tamiami aquifer is composed primarily of gray limestone. It consists of sandy, shelly limestone and calcareous sandstone and generally occurs in the lower part of the Tamiami Formation (Reese 2000).

In northern Lee County where the Tamiami Confining Unit is absent or insignificant, the Lower Tamiami aquifer is part of the unconfined water table aquifer (Marco Water Engineering, Inc. and Ecology and Environment, Inc. 2006). This means that no significant Aquitard Layer 1 exists in the Tidal Caloosahatchee Subwatershed. Thus, Aquifer Layer 1 and Aquifer Layer 2 are combined as one layer, the water table aquifer. Only the unconfined aquifer (water table aquifer) plays a significant role of impact on surface water. In this modeling effort, only the water table aquifer is simulated. The assumption made here is that the leakage from the unconfined aquifer (water table aquifer) to the confined aquifer (Aquifer Layer 3) through Aquitard Layer 2 is small enough to be ignored.

The bottom elevation GIS format of Aquifer Layer 2 generated by BEM System, Inc. (2003), was adapted as the water table aquifer bottom elevation for groundwater flow simulation module input. **Figure D-8** shows the water table aquifer bottom elevation.

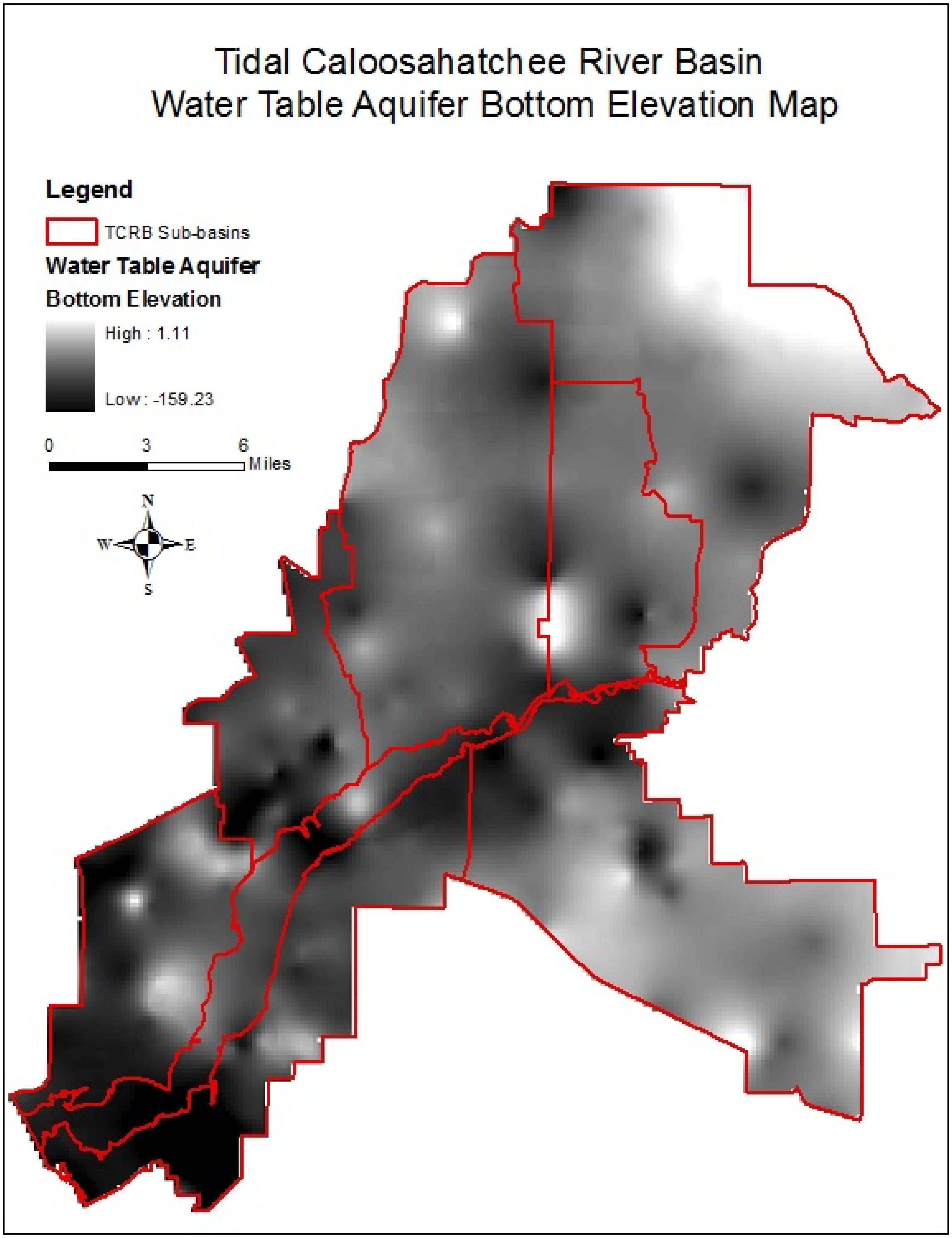

Figure D-8. Water table aquifer bottom elevation map for the Tidal Caloosahatchee Subwatershed. (Notes: Units are ft NAVD88. The Tidal Caloosahatchee Subwatershed is referred to as the Tidal Caloosahatchee River Basin on the map.)

Rainfall and Evapotranspiration

Rainfall is major driving force in the WaSh Model. There is a high spatial variability in daily rainfall due to the localized nature of conventional storms in the CRE MFL Watershed (Flaig and Capece 1998). The prevalence of convective and tropical disturbance in South Florida during the wet season presents a challenge in that the current rain gage network may not fully capture rain events that demonstrate high spatial variability (Skinner et al. 2009). Rainfall data based on Next Generation Radar (NEXRAD) data from the United States National Weather Service provides complete spatial coverage of rainfall amounts for the State of Florida. The accuracy of NEXRAD data is enhanced when adjusted using the local rain gage data (Huebner et al. 2003, Skinner 2006, 2009). The precision for the gage-adjusted radar is considered to be the same as standard rain gage precision.

The NEXRAD coverage for the SFWMD area is represented by a grid with a resolution of 2 km by 2 km. The rainfall amounts are stored in 15-minute intervals for the period of January 1, 1996, to present. This 15-minute rainfall data were retrieved from the SFWMD DBHYDRO database as model input.

Daily potential evapotranspiration (PET) data was used in WaSh model and obtained from the DBHYDRO database for model development.

CRE and Tributaries

The CRE has a number of tributaries located downstream of the S-79 structure that drain water into the estuary. The water released from S-79 eventually drains downstream and enters San Carlos Bay through the outlet at Shell Point. These tributaries are (1) Telegraph Creek, (2) Orange River, (3) Popash Creek, (4) Billy’s Creek, (5) Hancock Creek, (6) Whiskey Creek/Canal L, (7) Trout Creek, (8) Stroud Creek, (9) Daughtrey Creek, (10) Powell Creek, (11) Marshpoint Creek, (12) Bayshore Creek, (13) Cape Coral Canal System (San Carlos/Courtney Canal, Plato Canal, Mackinac Canal, and Meade/Honolulu Canal), (14) Manuels Branch, (15) Winkler Canal, (16) Deep Lagoon, and (17) other small canals and ditches (**Figure D-9**). Flow routing through this channel network is simulated by one-dimensional fully dynamic wave equations (St. Venant equations). Stage and flow at the outlet of tributaries (1) to (6) have been monitored starting around the end of 2007 or beginning of 2008 to March 2013 through a joint effort of USGS, FDEP, and SFWMD. Along the main channel, three stage and flow stations (S-79, Marker 52, and Shell Point) have long-term measured stage and flow data available. **Figure D-9** shows the location of these monitoring sites. All this measured information was used in model calibration and verification.

Figure D-9 also shows the USGS surficial aquifer groundwater stage monitoring sites that were used for water table comparison in model calibration and verification.

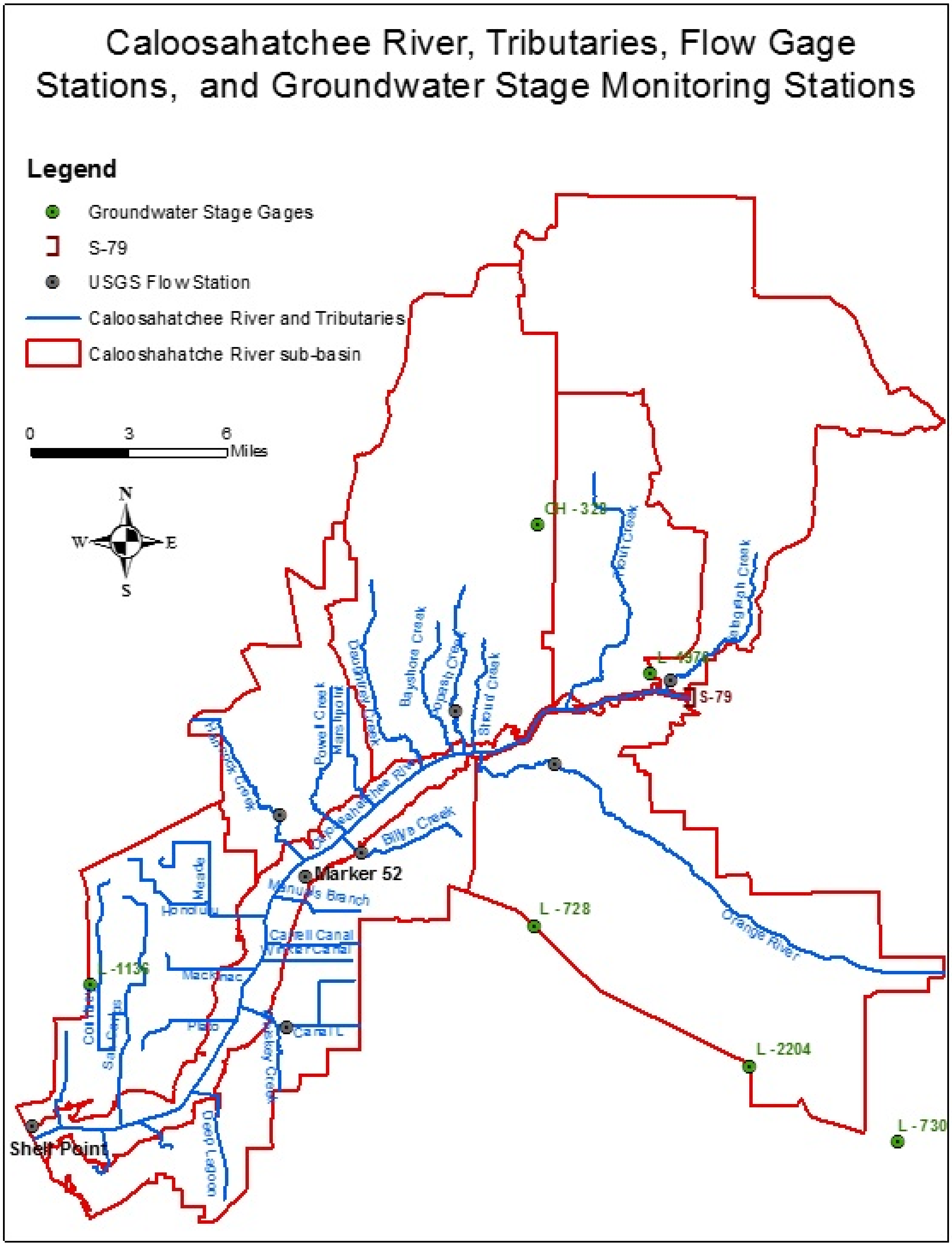

Figure D-9. CRE tributaries, flow gauge stations, and groundwater stage monitoring stations.

MODEL SETUP

The project domain, the Tidal Caloosahatchee Subwatershed, was discretized into 1,434 grid cells with 3,000-ft by 3,000-ft resolution while the main channel and tributaries were discretized into 467 segments with length of 2,000 ft (**Figure D-10**).

The spatial model input data presented in the Model Input Data section were overlaid on the grid cells. These overlaid data include topographic elevation, land use data, soil type data, and surficial aquifer bottom elevation. Model parameters for each cell are initialized based on those data and the knowledge obtained from the model application for the St. Lucie Estuary Watershed. NEXRAD rainfall data and PET data are assigned to each grid cell through the ArcGIS WaSh Model GUI tool.

The CRE main channel bathometry survey data were used as cross-section data. The tributaries cross-section data were obtained from the MIKE SHE model, an integrated hydrological modeling system for building and simulating surface water and groundwater flow (DHI Water & Environment 2002).

Various time steps were used in different simulation module components: 1 hour for the hydrologic module, 1 day for the groundwater flow module, and 30 minutes for the channel flow routing. Model output is as a daily time interval.

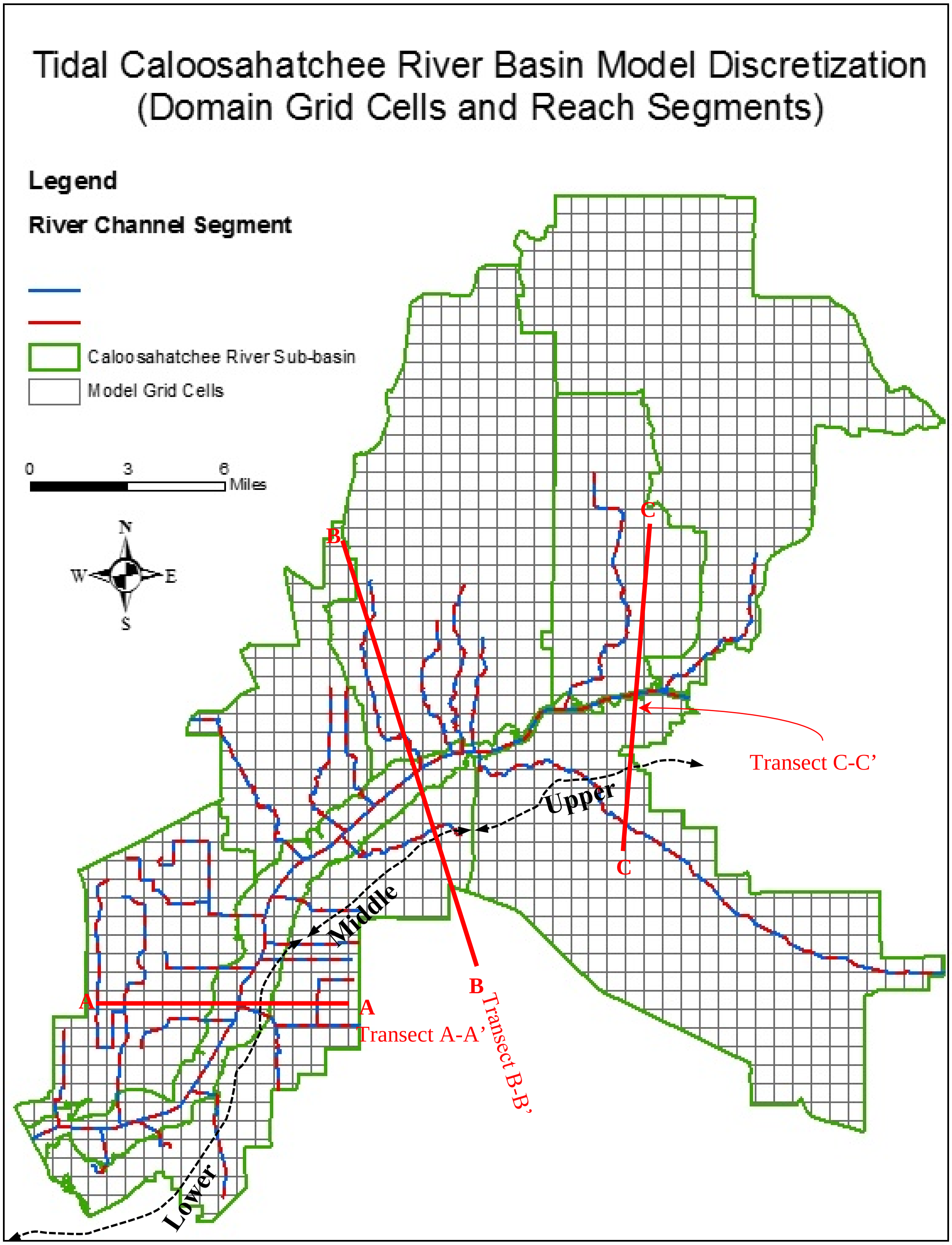

Figure D-10. Model discretization map for the Tidal Caloosahatchee Subwatershed. (Note: The Tidal Caloosahatchee Subwatershed is referred to as the Tidal Caloosahatchee River Basin on the map.)

BOUNDARY CONDITIONS

For surface water, the S-79 structure release is the boundary inflow to the CRE main channel and the tide stage at Shell Point is the downstream boundary condition for the model numerical solution. No flow exchange is assumed through the basin boundary for both surface water and groundwater.

MODEL CALIBRATION

The model was calibrated by traditional manual trial-and-error method using meteorological and hydrologic data (NEXRAD rainfall, PET, surficial groundwater table, and measured flow along main channel and tributaries) from 2008 to 2010. Model calibration is the process of adjusting model parameters to obtain model output to better match the observed values. Model performance was evaluated by four statistics, which are as follows:

- Bias

$$Bias = \frac{\sum_{i=1}^{n}\left(Q_{m,i} - Q_{s,i}\right)}{n} \qquad \boldsymbol{D.24}$$

- Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Q_{m,i} - Q_{s,i})^2}{n}} \qquad \boldsymbol{D.25}$$

- Coefficient of Determination (R^2)

$$R^2 = \left[\frac{\sum_{i=1}^{n}(Q_{m,i} - \overline{Q}_m)\left(Q_{s,i} - \overline{Q}_s\right)}{\sqrt{\sum_{i=1}^{n}(Q_{m,i} - \overline{Q}_m)^2 \sum_{i=1}^{n}(Q_{s,i} - \overline{Q}_s)^2}}\right]^2 \qquad \boldsymbol{D.26}$$

- Nash-Sutcliffe Efficiency (NSE; Nash and Sutcliffe 1970)

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{m,i} - Q_{s,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{m,i} - \overline{Q}_m\right)^2} \qquad \boldsymbol{D.27}$$

where

$Q_{m,i}$ = ith measured value

$Q_{s,i}$ = ith simulated value

$\overline{Q}_m$ = mean of measured values

$\overline{Q}_s$ = mean of simulated values

In the calibration process, the four statistics from **Equations D.24** through **D.27** with visual comparison of hydrographs were utilized to determine whether the model achieves better fit or not. Manual calibration usually requires a lot of experience and effort, but a good fit between the simulation and the observed data is possible. A GUI with Visual Basic for Applications embedded in Microsoft Excel was developed to assist with the model calibration (**Figure D-11**). This GUI allows modelers to load measured data and model output, enter a simulation time period to easily compute model performance statistics for model evaluation, create/view hydrographs, and view model parameters. The current version tool can calculate model performance statistics and creates hydrographs for eight sites where measured flows are available.

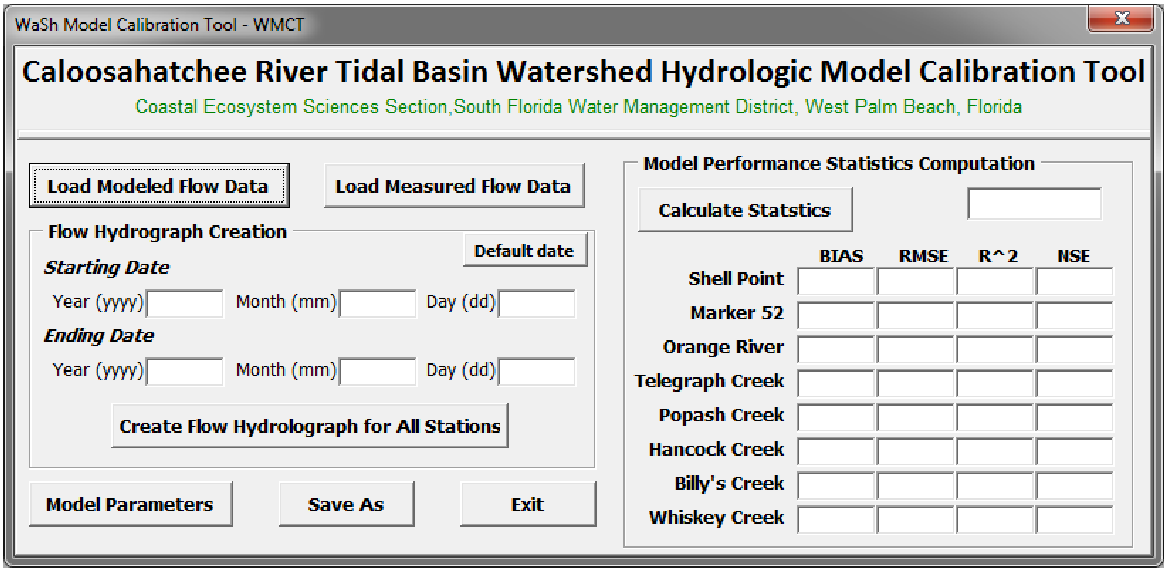

Figure D-11. Caloosahatchee River Tidal Basin Watershed Hydrologic Model Calibration Tool. (Note: The Caloosahatchee River Tidal Basin is the same as the Tidal Caloosahatchee Subwatershed.)

The model calibrated parameters are from three modules: surface hydrologic (PWATER/IWATER), river hydraulic, and groundwater flow. Initial model parameters for the surface hydrologic model were obtained from the St. Lucie Estuary Water Quality Model (URS, Inc. 2008b). Calibration were mainly focused on the following model parameters: interception storage capacity (CEPSC), upper zone nominal storage (UZSN), Manning's n for land surface (NSUR), interflow recession constant (IRC), interflow coefficient (INTFW), lower zone evaporation potential (LZETP), lower zone nominal storage (LZSN), infiltration rate (INFILT), parameter in infiltration functions (INFEXP and INFILD), groundwater evaporation potential (AGWETP), PET (monthly) coefficient, land use drainage pump rates (CANPMPPARM), pump depths (PMP_UC and PMP_LC), and canal conductance (CAN_CONDUCTANCE). The definition of these parameters are referred to **Attachment D-1** and also given in **Table D-5**. The complete calibrated hydrologic module parameters are listed in **Attachment D-2**.

Table D-5. Calibrated surface hydrologic module parameters and descriptions.

HSPF PWATER Parameter	Description
CEPSC	Interception storage capacity (inches)
UZSN	Upper zone nominal storage (inches)
NSUR	Manning's n for land surface
IRC	Interflow recession constant
INTFW	Interflow coefficient
LZETP	Lower zone evaporation potential (fraction)
LZSN	Lower zone nominal storage (inches)
INFILT	Infiltration rate (inches per hour [/hr])
INFEXP	Parameter in infiltration function
INFILD	Parameter in infiltration function
AGWETP	Groundwater evaporation potential (fraction)
PET Coefficient	Evaporation scale factor (fraction, varies by month)
CANPMPPARM	Land use tertiary canal drainage pump rate (inches/hr)
PMP_UC	Tertiary canal depth for triggering pump (ft)
PMP_LC	Tertiary canal depth for stopping pump (ft)
CAN_CONDUCTANCE	Tertiary canal bed conductance (ft/day)

The model parameters calibrated for hydraulic module are Manning's roughness and river bottom conductance. Calibrated Manning's roughness varies from 0.03 to 0.045. The calibrated river/channel bottom conductance is from 0.5 to 0.75 feet per day (ft/day).

The groundwater flow module calibration was focused on soil saturated hydraulic conductivity and soil porosity. In the final model, 25 ft/day of hydraulic conductivity and 0.3 of soil porosity were used.

The final model performances for calibration quantified by four statistics are presented in **Table D-6** for eight flow gage stations. Their hydrograph comparisons between measured and simulated flow are presented in **Attachment D-3**.

From **Table D-6**, we can see the model has very good performance in model calibration. For two major rivers, Orange River and Telegraph Creek, the R^2 between simulated and measured flow are 0.87 and 0.84, respectively, while NSE is 0.8 and 0.84, respectively. For Shell Point, R^2 and NSE are 0.8 and 0.75, respectively. The rest of the tributaries have $R^2 > 0.66$ and NSE > 0.57. Bias and RMSE are relatively small for all sites. Mean value and standard deviation of observed and simulated flow were also calculated and shown in the table. Comparison plots of accumulative flow are presented in **Figure D-3-9** in **Attachment D-3**. It is apparent that model reasonably reproduced flow variation and flow pattern.

After the model parameters were calibrated with measured flow for gaged subbasins, the parameters were applied to ungaged subbasins mainly based on land use types. For example, the model parameters calibrated in Orange River for urban land use were applied to urban land use in the Cape Coral Subbasin.

Table D-6. Model performance for model calibration.

Subbasin	BIAS (cfs) [a]	RMSE (cfs)	R^2	NSE	Mean ± SD (observed)	Mean ± SD (simulated)
Shell Point	-717	1,882	0.8	0.75	1,264 ± 3,796	1,976 ± 3,877
Marker 52	92	1,854	0.66	0.66	1,935 ± 3,173	1,843 ± 2,665
Orange River	-18	59	0.87	0.8	109 ± 133	120 ± 137
Telegraph Creek	-3	45	0.84	0.84	61 ± 114	63 ± 108
Popash Creek	-5	13	0.64	0.57	7 ± 20	14 ± 17
Hancock Creek	-4	17	0.67	0.65	18 ± 28	19 ± 24
Billy's Creek	-3	16	0.68	0.67	16 ± 28	20 ± 21
Whiskey Creek	-1	8	0.73	0.72	10 ± 15	11 ± 10

a. cfs – cubic feet per second.

MODEL VERIFICATION

The model was verified using meteorological and hydrologic data from 2011 through 2012. The model performances for verification are presented in **Table D-7**. Hydrograph comparisons between measured and simulated flow for model verification are given in **Attachment D-3**.

Table D-7. Model performance for model verification.

Sub-Basin	BIAS (cfs) [a]	RMSE (cfs)	R^2	NSE	Mean ± SD (observed)	Mean ± SD (simulated)
Shell Point	-251	1,632	0.8	0.78	1,354 ± 3,488	1,597 ± 3,487
Marker 52	-356	1,919	0.56	0.55	1,097 ± 2,851	1,449 ± 2,159
Orange River	-38	78	0.61	0.12	67 ± 92	95 ± 112
Telegraph Creek	5	41	0.82	0.79	64 ± 89	58 ± 97
Popash Creek	0	15	0.80	0.66	13 ± 25	14 ± 14
Hancock Creek	-6	19	0.57	0.52	12 ± 28	17 ± 21
Billy's Creek	-3	19	0.65	0.64	16 ± 31	22 ± 23
Whiskey Creek	-3	12	0.51	0.4	10 ± 15	12 ± 12

a. cfs – cubic feet per second.

b. This low NSE is partially due to ungagued flow.

The model verification is good at most sites. **Table D-7** shows that $R^2 \geq 0.8$ and NSE ≥ 0.66 for Shell Point, Telegraph Creek, and Popash Creek, indicating the model performs very well in verification for these sites. The model has fair performance for Billy's Creek and Orange River in terms of R^2 (0.65 and 0.61, respectively). For Whiskey Creek, Marker 52, and Hancock Creek, the R^2 for model verification is between 0.51 to 0.57, meaning very fair performance. Based on communication with USGS staff who conducted flow measurements, the measured flow at these three sites have less reliability (Patino, personal communication, 2014). For example, the measured flow at Whiskey Creek does not reflect the leakage at both sides of a weir. Tidal influences affect filtering at the Hancock Creek and Marker 52 sites. The worse NSE (0.12) is at Orange River. The simulated flow is much higher than measured flow during July to September (**Attachment D-3**, **Figure D-3-3**). To exclude the possibility caused by error existing in rainfall data, the NEXRAD rainfall used in the simulation was verified and compared with the rainfall from surface ground gages. No significant bias was found between the two rainfall data sets. Then, we conducted a hydrology connection investigation. We found there are two external connections to the Orange River Subbasin, one culvert connected to a canal located at its east side, and four culverts connected to a big canal at its north side. Unfortunately, there is no flow data available for these culverts. There is a possibility that some flow was released to the east or north through those culverts that is not represented in the model and causing low NSE (0.12). Mean value and standard deviation of observed and simulated flow were also calculated and shown in the table. Comparison plots of accumulative flow are presented in **Figure D-3-10** in **Attachment D-3**. Generally, the model was able to reasonably predict flow variation and flow pattern for the verification time period.

LONG-TERM SIMULATION 1968- 2012

With the calibrated and verified WaSh model, a long-term simulation was conducted for the 1967–2012 time period. The most recent land use data of 2012 was used for this long-term simulation. The rainfall data, originally developed for the South Florida Water Management Model (SFWMM), was used for 1968 to 2001 while NEXRAD data was used for 2002 to 2012. PET data obtained from DBHYDRO was used for the simulation. The purpose of the simulation was to determine the surface water and groundwater flow to the Tidal Caloosahatchee Subwatershed with a variety of climatic condition through 46 years based on current land use. From the simulation results, the surface water and groundwater flow to the Tidal Caloosahatchee Subwatershed, including annual average, dry season average, and wet season average for upper stream, middle stream, lower stream, and whole channel of the CRE, were calculated and presented in **Table D-8**.

Table D-8. Simulated surface water and groundwater flow from the Tidal Caloosahatchee Subwatershed to the CRE with current land use and measured flow at S-79 (average of 1967–2012).

	Flow					
	All Seasons		Dry Seasons [a]		Wet Seasons [a]	
	(cfs) [b]	%	(cfs)	%	(cfs)	%
Tidal Caloosahatchee Subwatershed surface runoff	380.5	17.7%	221.8	15.0%	537.0	19.0%
Tidal Caloosahatchee Subwatershed groundwater seepage	49.8	2.3%	23.0	1.6%	76.3	2.7%
S-79 inflow	1,722.4	80.0%	1,228.7	83.4%	2,209.2	78.3%
Total	**2,152.7**		**1,473.5**		**2,822.5**	

a. Wet season is May–October and dry season is November–April.
b. cfs – cubic feet per second.

CRE MFL reevaluation also requires an assessment for future land use conditions. Thus, another long-term simulation for the 1967–2012 period is conducted with future land use data. Future land use projections to 2040 were developed using a combination of permitted boundaries, public lands, county comprehensive plans, and Florida Statewide Agricultural Irrigation Demand (FSAID) data. Current land use, updated to 2012, was used as the base land use GIS layer. All of the mentioned data sets were incorporated into the 2012 data set and used to query and establish future land use Florida Land Use, Cover, and Forms Classification System (FLUCCS) codes for urban, conservation, water storage, and agriculture land use types. The average surface and groundwater inflow based on this long-term simulation results are presented in **Table D-9** with S-79 measured flow for comparison.

Table D-9. Simulated surface water and groundwater flow from the Tidal Caloosahatchee Subwatershed to the CRE with future land use and measured flow at S-79 (average of 1967–2012).

	Flow					
	All Seasons		Dry Seasons [a]		Wet Seasons [a]	
	(cfs) [b]	%	(cfs)	%	(cfs)	%
Tidal Caloosahatchee Subwatershed surface runoff	379.1	17.6%	221.2	15.0%	534.8	19.0%
Tidal Caloosahatchee Subwatershed groundwater seepage	47.8	2.2%	21.3	1.5%	74.0	2.6%
S-79 inflow	1,722.4	80.1%	1,228.7	83.5%	2,209.2	78.4%
Total	2,149.3		1,471.2		2,818.0	

a. Wet season is May–October and dry season is November–April.
b. cfs – cubic feet per second.

Comparing **Table D-8** with **Table D-9**, we can see that the difference of inflow from the Tidal Caloosahatchee Subwatershed is very minor between the 2012 land use condition and the future land use condition. The reason is the land use changes from 2012 to the future (2040) are minor. The major land use changes are a 3% increase in agriculture, 3% decrease in upland forest, and 1.2% increase in wetland. Apparently, this minor land use change leads to little change in inflow from the Tidal Caloosahatchee Subwatershed.

INTERACTION BETWEEN CRE AND GROUNDWATER

With the developed WaSh Model, the interaction between CRE main channel flow and groundwater was explored. For this purpose, three transects were identified to investigate the variation of groundwater associated with main channel flow: Transect $A - A'$ in the lower estuary, Transect $B - B'$ in the middle estuary, and Transect $C - C'$ in the upper estuary (**Figure D-10**). The three estuary segments are defined as follows: (1) lower estuary from the SR-41 Bridge to Shell Point; (2) middle estuary from the I-75 Bridge to the SR-41 Bridge (right upstream of the confluence of Hancock Creek); and (3) upper estuary from the S-79 structure to the I-75 Bridge (right downstream of the confluence of Orange River).

Table D-10 presents the groundwater seepage along upper, middle, and lower estuary segments in all seasons, dry seasons, and wet seasons as a long-term average for the 1967–2012 period. Groundwater seepage during the dry season is generally small (total of 23 cubic feet per second [cfs]) with almost even distribution of 7 to 8 cfs along all segments. During the wet season, total seepage flow (76 cfs) to the estuary is more than triple of that of the dry season with it being lower in the upper and middle estuary segments and higher in the lower estuary segment. The primary land use type in the drainage area of the lower estuary segment is urban with lower topography. In the wet season, the community ponds, lakes, ponds, and canals located in urban drainage area will be filled by water, which raises groundwater stage and leads to more groundwater seepage to the estuary. In the dry season, the groundwater stage is significantly reduced in the subsurface with low topography and results in trivial groundwater seepage to the estuary.

Table D-10. Groundwater flow to the Tidal Caloosahatchee Subwatershed along upper, middle, and lower estuary segments in dry, wet, and all seasons based on the simulation from 1967 to 2012.

Segment	Groundwater Flow (cfs)		
	All Season	Dry Season [a]	Wet Season [a]
Upper estuary	15.0	8.8	21.1
Middle estuary	14.0	7.2	20.8
Lower estuary	20.8	7.0	34.4
Total	**49.8**	**23.0**	**76.3**

a. Wet season is May- October and dry season is November- April.

Groundwater stage profiles along the selected three transects are presented in **Attachment D-5 (Figures D-5-1** through **D-5-3)**. The figures in this attachment show the ground surface elevation, river estuary bottom elevation, and groundwater stage on the starting point of wet season in 2011 (June 14, 2011), the highest groundwater stage in the wet season (October 30, 2011; when the wet season ended and dry season started), and the dry season ending point (May 12, 2012). The groundwater stage went up from June 14, 2011, to the highest point on October 30, 2011, and then fell back on May 12, 2012 to very close to the stage on June 14, 2011. From the profiles, the highest groundwater stage on October 30, 2011, was higher than ground surface elevation in some locations (so there was ponding). This increase to decrease cycle of groundwater stage from the wet season through the dry season of May 2011 to April 2012 can also be seen in the figures presented in **Attachment D-4**. The change of groundwater stage through the wet and dry season of 2011–2012 ranges around 2 to 5 ft.

The daily groundwater seepage actually fluctuates between negative and positive values due to the impact of tide. **Figure D-4-4** in **Attachment D-4** shows the daily groundwater seepage/recharge, surface runoff, and summation of them to the estuary.

Combining groundwater with surface water runoff, the total freshwater inflow to the CRE from the Tidal Caloosahatchee Subwatershed is 427 cfs (groundwater inflow 48 cfs plus surface water inflow 379 cfs) from 1967 to 2012, which is ~20% of total inflow to the estuary (80% is from S-79, i.e., runoff from the C-43 Watershed and Lake Okeechobee).

The surface runoff coefficient of 2008–2012 was calculated based on the long-term simulation results (**Figure D-12**), which ranges from 0.197 for a dry year (2009) to 0.284 for a wet year (2008).

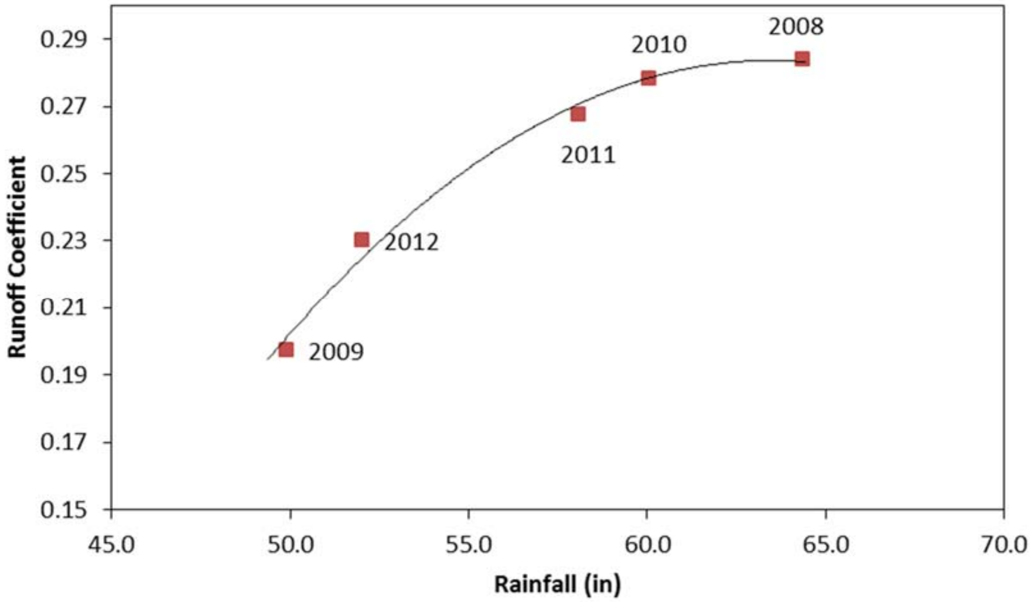

Figure D-12. Plot of runoff coefficient for 2008-2012.
(Note: in – inches.)

SUMMARY AND DISCUSSION

A watershed hydrologic model was developed for the Tidal Caloosahatchee Subwatershed. The model was calibrated using data from 2008 through 2010 and verified with the data of 2011–2012. The model performance was evaluated by bias, root mean square error (RMSE), coefficient of determination (R^2), and Nash-Sutcliffe efficiency (NSE). Generally, the model performance was encouraging. Simulated flows at eight monitoring sites have an R^2 of 0.64 to 0.87 for calibration and 0.51 to 0.82 for verification. The NSE is 0.57 to 0.84 for calibration and 0.12 to 0.78 for verification. Measured data at Market 52, Popash Creek, and Whiskey Creek were identified as low quality. Relatively poor model performances are found at these sites.

Groundwater flow is an important part in South Florida hydrologic processes. The PWATER module of HSPF was modified in this project to accommodate the high water table with significant fluctuation in South Florida. Unfortunately, measured daily groundwater stage data is not available for model calibration and verification in the study area. The measured maximum groundwater water stages at three locations and monthly (sometimes bimonthly) measured daily maximum stages for a specific day at the other three locations are available. These data were used to make comparison plots with simulated data to visually assist model calibration and verification. These hydrograph comparisons are presented in **Attachment D-4**. These data played an important role for groundwater flow module calibration. The model performance statistics were not calculated for these stations since they are not same type of data (measured daily maximum versus daily model output), only applying visual comparison to assist on calibration. Among six groundwater stage monitoring sites, the L730 well is located outside of the study domain. This water table data was used as a reference to help check the simulated groundwater stages of areas southwest of the Orange River Subbasin, which are closest to the L730 site (**Figure D-9**). From the comparisons given in **Attachment D-4**, the simulated groundwater stage showed great improvement with newly modified Fortran codes of the WaSh Model.

Overall, the model performance is encouraging both in surface flow (**Attachment D-3**) and groundwater stage (**Attachment D-4**).

The developed model was used to conduct a 46-year long-term simulation from 1967 to 2012 with both current (2012) and future (2040) land use conditions. With the long-term simulation results, the groundwater seepage flow was computed for lower, middle, and upper estuary segments. Three transects were identified to investigate the groundwater stage variation. The groundwater stage profile for the three transects are provided in **Attachment D-5**. Daily freshwater inflow time series were obtained (for example, **Figure D-5-4** in **Attachment D-5** presents the time series of 2011).

A period of record of 1967 to 2005 is applied to the CRE MFL update. The time series of inflow from the Tidal Caloosahatchee Subwatershed to the CRE for the same period of record based on the above long-term simulation were provided as model input to the Curvilinear Hydrodynamic Three-dimensional Model (CH3D). With this inflow data as input, CH3D was able to achieve excellent simulation result, for instance, R^2 is 0.95 for the salinity simulation (see the *CH3D CRE Hydrodynamic/Salinity Model* section in **Chapter 7**).

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ATTACHMENT D-1: ALGORITHMS OF PWATER MODULE IN HSPF

The PWATER module in HSPF is used to simulate hydrologic processes involved in a pervious land segment. Its algorithms summarized here are based on the *Hydrologic Simulation Program – Fortran, User's Manual for Version 11* (Bicknell et al. 1997), which is originally from *Stanford Watershed Model IV* (Crawford and Linsley 1966).

Interception

This refers to the rainfall intercepted by vegetal or other ground cover. The rainfall accounted for here includes regular rainfall, snow, and irrigation water. The formula to calculation interception is as follows:

$$S_{INTCEP}(i) = S_{INTCEP}(i-1) + P(i) \qquad \boldsymbol{D.1.1}$$

$if S_{INTCEP} > S_{INTCEP}$

$$P_{eff}(i) = S_{INTCEP}(i) - S_{INTCEP} \qquad \boldsymbol{D.1.2}$$

$$S_{INTCEP}(i) = S_{INTCEP} \qquad \boldsymbol{D.1.3}$$

$if\ S_{INTCEP} \leq S_{INTCEP}$

$$P_{eff}(i) = 0 \qquad \boldsymbol{D.1.4}$$

where

$S_{INTCEP}(i)$ = Interception storage at time step i (inches)

$P(i)$ = Rainfall at time step i (inches)

$S_{INTCEPC}$ = Interception capacity (inches)

$P_{eff}(i)$ = Effective rainfall after interception at time step i (inches)

Infiltration and Potential Direct Runoff

The effective rainfall after interception reaches land surface, and then either moves toward stream channels as surface runoff or infiltrates into the subsurface. Infiltration is calculated based on soil water storage. Soil water storage is broken into two zones, an upper zone storage (S_{UZ}), which is a relatively shallow zone where water could be removed by gravity drainage or evaporation, and lower zone storage (S_{LZ}), where water could be removed by vegetation transpiration. The upper and lower zone storages, despite their names, were defined by their behavior rather by their physical location (Crawford and Burges 2004). The mechanism behind this is the way water is stored in the soil.

Water is stored in soil as adhesion water, cohesion water, and gravitational water. Adhesion water is electrically bonded to soil particles and is immobile except at very high temperatures (in drying ovens). Cohesion water is bonded in soil by capillary forces and weaker electrical forces. Cohesion water is roughly equal to the "available water", the difference between the wilting point and filled capacity. Gravitational water will drain from soils in the unsaturated zone unless drainage is inhibited. Gravitational water can be defined as being present in macropores while cohesion water is present in micropores (Hydrocomp Inc. and AQUA TERRA Consultants 1996). In HSPF, cohesion water is stored in the "lower zone" storage, while gravitational water is stored in the "upper zone" and interflow storages.

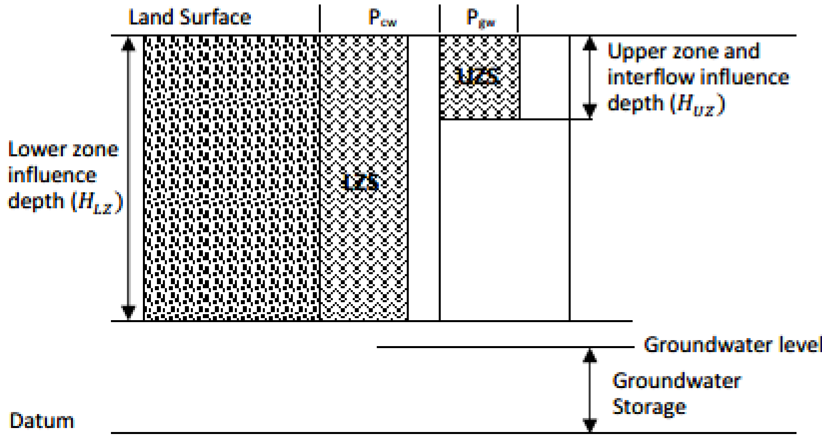

Figure D-1-1. Sketch of soil moisture in the unsaturated zone.
(Modified from Hydrocomp, Inc. and AQUA TERRA Consultants 1996.)

Influence depth in **Figure D-1-1** is the maximum depth where soil moisture varies seasonally due to ET. Soil moisture within the influence depth is hydrologically active. The depths of influence below the land surface for the soil moisture storages are defined as follows:

$$H_{LZ} = \frac{2.5S_{LZN}}{P_{cw}} \qquad \textbf{D.1.5}$$

$$H_{UZ} = \frac{4S_{UZN}}{P_{gw}} \qquad \textbf{D.1.6}$$

where

H_{LZ} = Lower zone influence depth (inches)
H_{UZ} = Upper zone influence depth (inches)
S_{LZN} = Lower zone nominal storage (inches)
S_{UZN} = Upper zone nominal storage (inches)
P_{cw} = Porosity of cohension water (micropores)
P_{gw} = Porosity of gravitational water (macropores)

The constants 2.5 and 4 in **Equations D.1.3** and **D.1.4**, respectively, were derived from the methods used in HSPF to compute the capture of percolating water into the lower and upper zones. They are included in the model as parameters to allow investigation of sensitivity to these quantities.

Unique algorithms were developed to simulate both the temporal variation of infiltration rate as a function of soil moisture and the spatial variation of infiltration over the land segment (Bicknell et al. 1997). The equations representing the dependence of infiltration on soil moisture are based on Philips infiltration equation (Philips 1957). Infiltration capacity is a function of both the fixed and variable characteristics of a watershed. Fixed characteristics include primarily soil permeability and land slopes, while variables are soil surface conditions and soil moisture content. Fixed and variable characteristics vary spatially over the land segment, resulting in the cumulative frequency distribution of infiltration capacity (**Figure D-1-2**).

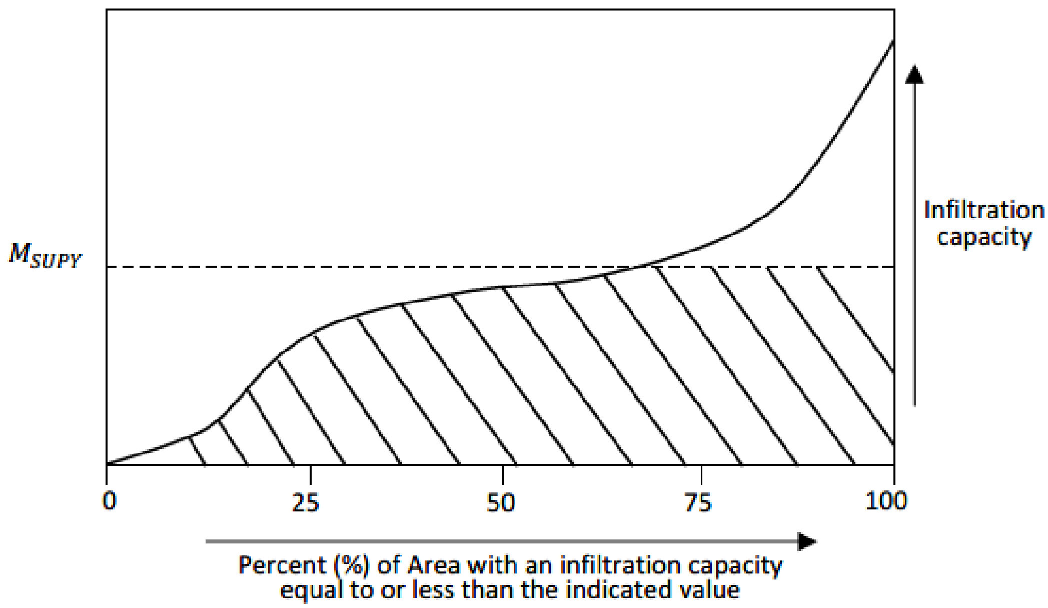

Figure D-1-2. Cumulative frequency distribution of infiltration capacity.

Assuming the moisture supply available on a land segment is M_{SUPY} during a time interval, we can usually obtain the cumulative frequency distribution of infiltration capacity for the same time interval as shown in **Figure D-1-2**, in which the total volume of infiltration will be proportional to the shaded area. The remaining area, between the effective rainfall line and the infiltration capacity curve, represents the volume remaining on land surface that may not reach a stream channel since it may be diverted to temporary storages, and it remains subject to infiltration (Crawford and Linsley 1966). In HSPF, the cumulative frequency distribution of infiltration capacity in **Figure D-1-2** is assumed to be linear from zero to a maximum value as shown in **Figure D-1-3**.

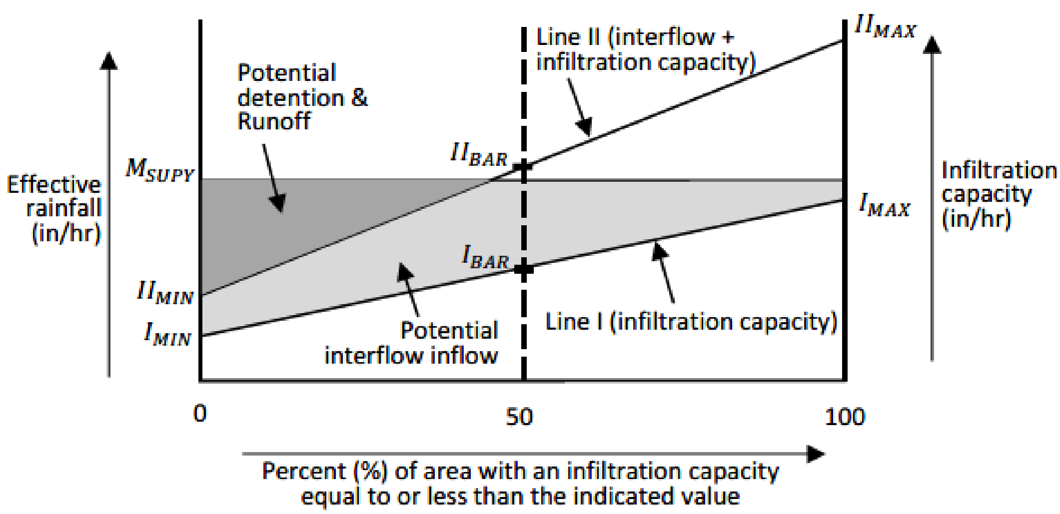

Figure D-1-3. Linear cumulative frequency distribution of infiltration capacity for determination of infiltration and interflow inflow.
(Notes: Modified from Bicknell et al. 1997. in/hr – inches per hour.)

The infiltration capacity is divided into two regions in **Figure D-1-3** with two linear cumulative frequency distribution of infiltration capacities, Line I and Line II. In the region under Line I, all infiltrated water is assumed to move into the lower zone and groundwater storages. The infiltration in the region between Line I and Line II is assumed to contribute to interflow. The variables for Line I shown in **Figure D-1-3** are calculated by the following equations:

$$I_{BAR} = \frac{f_c}{\left(\frac{S_{LZ}}{S_{LZN}}\right)^c} F_{frozen} \qquad \textbf{D.1.7}$$

$$I_{MAX} = R_I I_{BAR} \qquad \textbf{D.1.8}$$

$$I_{MIN} = I_{BAR} - (I_{MAX} - I_{BAR}) \qquad \textbf{D.1.9}$$

$$R_{II-I} = C_{INTFL}\ 2^{\left(\frac{S_{LZ}}{S_{LZN}}\right)} \qquad \textbf{D.1.10}$$

where

I_{BAR} = mena infiltration capacity over the land segment (inches/hr)

f_c = infiltration with lower zone nominal storage (inches/hr)

c = exponent parameter greater than one

F_{frozen} = factor to account for frozen ground effects, if applicable

I_{MAX} = maximum infiltration capacity (inches/hr)

I_{MIN} = mimimum infiltation capacity (inches/hr)

R_I = parameter giving the ratio of maximum to mean infiltration capacity over the land segment

R_{II-I} = ration of the ordinates of Line II to Line I

C_{INTFL} = interflow parameter

The moisture supply available to land segment (M_{SUPY}) includes the effective rainfall (P_{eff}) from interception storage, initial surface runoff storage (S_{SUR}) on the land segment, and other lateral inflow (I_{SURL}) to the land segment, such as irrigation water from outside. Thus, we get **Equation D.1.11**:

$$M_{SUPY} = P_{eff} + S_{SUR} + I_{SURL} \qquad \textbf{D.1.11}$$

The infiltration to lower zone and groundwater and potential direct runoff are computed as follows:

$if\ M_{SUPY} \leq I_{MIN}$

$$f = M_{SUPY} \qquad \textbf{D.1.12}$$

$$R_{PDR} = 0 \qquad \textbf{D.1.13}$$

$if\ M_{SUPY} \geq I_{MAX}$

$$f = 0.5(I_{MIN} + I_{MAX}) \qquad \textbf{D.1.14}$$

$$R_{PDR} = M_{SUPY} - f \qquad \textbf{D.1.15}$$

$if\ I_{MIN} < M_{SUPY} < I_{MAX}$

$$R_{PDR} = \frac{0.5(P_{eff} - I_{MIN})^2}{I_{MAX} - I_{MIN}} \qquad \textbf{D.1.16}$$

$$f = M_{SUPY} - R_{PDR} \qquad \textbf{D.1.17}$$

where

f = infiltration into lower zone and groundwater storages (inches/hr)

R_{PDR} = potential direct runoff (inches/hr)

Infiltration into the lower zone and groundwater storages (f) is the region under Line I in **Figure D-1-3** while potential direct runoff (R_{PDR}) here is the grey area between Line I and moisture supply (M_{SUPY}) in **Figure D-1-3**, including both the dark grey and light grey areas. It will either enter upper zone storage or be available for either interflow or overland flow (Bicknell et al. 1997). The calculation for the dark grey and light grey areas will be addressed in later sections.

Upper Zone Inflow

The part of the potential direct runoff (R_{PDR}) calculated in the previous section will enter the upper zone as the function of upper zone soil moisture content, which is represented by the ratio of the storage of upper zone to it nominal storage. The fraction of potential direct runoff as upper zone inflow (F_{UZI}), i.e. the fraction retained by the upper zone storage, is calculated by the following:

$if \ \frac{S_{UZ}}{S_{UZN}} \leq 2$

$$F_{UZI} = 1 - \left(\frac{\frac{S_{UZ}}{S_{UZN}}}{2}\right)\left(\frac{1}{4 - \frac{S_{UZ}}{S_{UZN}}}\right)^{\left(3 - \frac{S_{UZ}}{S_{UZN}}\right)} \qquad \textbf{D.1.18}$$

$if \ \frac{S_{UZ}}{S_{UZN}} > 2$

$$F_{UZI} = \left(\frac{0.5}{\frac{S_{UZ}}{S_{UZN}} - 1}\right)^{\left(\frac{2S_{UZ}}{S_{UZN}} - 3\right)} \qquad \textbf{D.1.19}$$

Then, the upper zone storage inflow is calculated as follows:

$$I_{UZS} = R_{PDR}F_{UZI} \qquad \textbf{D.1.20}$$

Surface Detention/Runoff Inflow and Interflow Inflow

Potential direct flow is the region between Line I and moisture supply (M_{SUPY}) in **Figure D-1-3**, which is further divided by Line II into two parts: potential surface detention/runoff inflow (underneath both Line II and moisture supply but above Line I) and potential interflow inflow (above Line II but below moisture supply). The ordinates of Line II are found by multiplying the ordinates of Line I by the ratio of the ordinates of Line II to Line I, which is already computed in **Equation D.1.10**:

$$II_{MIN} = R_{II-I}I_{MIN} \qquad \textbf{D.1.21}$$

$$II_{MAX} = R_{II-I}I_{MAX} \qquad \textbf{D.1.22}$$

With II_{MIN} and II_{MAX} known, potential surface detention/runoff inflow (dark grey area in **Figure D-1-3**; R_{PSUR}) is computed following the same algorithm used from **Equations D.1.12** through **D.1.17**:

$if\ M_{SUPY} \leq II_{MIN}$

$$R_{PSUR} = 0 \qquad \boldsymbol{D.1.23}$$

$if\ M_{SUPY} \geq II_{MAX}$

$$R_{PSUR} = M_{SUPY} - 0.5(II_{MIN} + II_{MAX}) \qquad \boldsymbol{D.1.24}$$

$if\ II_{MIN} < M_{SUPY} < II_{MAX}$

$$R_{PSUR} = \frac{0.5(M_{SUPY} - II_{MIN})^2}{II_{MAX} - II_{MIN}} \qquad \boldsymbol{D.1.25}$$

Then, potential interflow inflow (R_{PINTFL}) is calculated by the following:

$$R_{PINTFL} = R_{PDR} - R_{PSUR} \qquad \boldsymbol{D.1.26}$$

Upper zone storage inflow computed in **Equation D.1.20** is assumed consist of the water from potential surface runoff/detention and potential interflow. The final interflow inflow and surface runoff/detention inflow are computed using a fraction of potential direct runoff as upper zone inflow (F_{UZI}) calculated in **Equations D.1.18** and **D.1.19**:

$$R_{SUR} = R_{PSR}(1 - F_{UZI}) \qquad \boldsymbol{D.1.27}$$

$$R_{INTFL} = R_{PINTFL}(1 - F_{UZI}) \qquad \boldsymbol{D.1.28}$$

Surface Runoff Routing

Surface runoff is treated as a turbulent flow process. It is simulated using the Chezy-Manning equation and an empirical that relates outflow depth to detention storage. A more detailed explanation and derivation can be found in Crawford and Linsley (1966). The surface runoff outflow is calculated by the following equations:

$$S_{SURE} = 0.00982\left(\frac{nL}{\sqrt{S}}\right)^{0.6} (R_{SUR} - S_{SUR})^{0.6} \qquad \boldsymbol{D.1.29}$$

$if\ R_{SUR} < S_{SURE}$

$$O_{SUR} = 1020T_h\left(\frac{\sqrt{S}}{nL}\right)\left(\frac{R_{SUR}}{1 + 0.6\left(\frac{R_{SUR}}{S_{SURE}}\right)^3}\right)^{1.67} \qquad \boldsymbol{D.1.30}$$

$if\ R_{SUR} \geq S_{SURE}$

$$O_{SUR} = 1020T_h\left(\frac{\sqrt{S}}{nL}\right)(1.6R_{SUR})^{1.67} \qquad \boldsymbol{D.1.31}$$

where

S_{SURE} = equilibrium surface detention storage for current supply rate

O_{SUR} = surface outflow (inches/hr)

T_h = total hours (hr) in time interval

n = Manning's roughness for the overland flow plane
L = length of the overland flow plane (ft)
S = slope of the overland flow plane (ft/ft)

After outflow form surface runoff storage, the surface runoff storage needs to be updated:

$$S_{SUR} = R_{SUR} - O_{SUR} \qquad \mathbf{D.1.32}$$

Interflow Outflow

The calculation of interflow outflow assumes a linear relationship to storage. Thus, outflow is a function of a recession parameter, inflow, and storage. Moisture that remains will occupy interflow storage. Interflow outflow is calculated and then interflow storage is updated by the following equations:

$$S_{INTFL}' = S_{INTFL} + R_{INTFL} \qquad \mathbf{D.1.33}$$

$if\ S_{INTFL}' > 0$

$$O_{INTFL} = \left(1.0 - \frac{1.0 - C_{rece}^{\left(\frac{T_h}{24}\right)}}{C_{rece}\, ln(C_{rece})}\right) R_{ITTFL} + \left(1.0 - C_{rece}^{\left(\frac{T_h}{24}\right)}\right) S_{INTFL} \qquad \mathbf{D.1.34}$$

$if\ S_{INTFL}' = 0$

$$O_{INTFL} = 0 \qquad \mathbf{D.1.35}$$

where
O_{INTFL} = interflow outflow (inches/hr)
C_{rece} = interflow recession parameter (1/day)
S_{INTFL} = interflow storage at the start of the interval (inches)

Then interflow storage is updated for the next time step use:

$$S_{INTFL} = S_{INTFL}' - O_{INTFL} \qquad \mathbf{D.1.36}$$

Percolation of Upper Zone

The upper zone receives inflow calculated in **Equation D.1.20** and leads to change of upper zone storage:

$$S_{UZ} = S_{UZ} + I_{UZS} \qquad \mathbf{D.1.37}$$

With updated storage in the upper zone, percolation may occur from the upper zone to the lower zone and groundwater. Water remaining in the upper zone is available for ET. Upper zone percolation takes place only when upper zone storage reaches a certain level, which is quantified by $\frac{S_{UZ}}{S_{UZN}} - \frac{S_{LZ}}{S_{LZN}} > 0.01$.

When this happens, the upper zone percolation (Q_{PERC}) is computed by the following empirical formula:

$$Q_{PERC} = min\left(S_{UZ}, 0.1 f_c F_{frozen} S_{UZN} \left(\frac{S_{UZ}}{S_{UZN}} - \frac{S_{LZ}}{S_{LZN}}\right)^3\right) \qquad \mathbf{D.1.38}$$

Then, the upper zone storage is updated as follows:

$$S_{UZ} = S_{UZ} - Q_{PERC} \qquad \textbf{D.1.39}$$

Lower Zone Inflow and Groundwater Inflow

The infiltration and percolation may enter the lower zone and groundwater storages. The fraction of water that enters the lower zone is based on the ration of lower zone storage to lower zone nominal storage. It is computed by the following equations:

$$if\ \frac{S_{LZ}}{S_{LZN}} < 1.0$$

$$F_{LZ} = 1.0 - \frac{S_{LZ}}{S_{LZN}}\left(\frac{1.0}{3.5 - \frac{1.5S_{LZ}}{S_{LZN}}}\right)^{\left(2.5-\frac{1.5S_{LZ}}{S_{LZN}}\right)} \qquad \textbf{D.1.40}$$

$$if\ \frac{S_{LZ}}{S_{LZN}} \geq 1.0$$

$$F_{LZ} = \left(\frac{1.0}{\frac{1.5S_{LZ}}{S_{LZN}} + .5}\right)^{\left(\frac{1.5S_{LZ}}{S_{LZN}}-0.5\right)} \qquad \textbf{D.1.41}$$

Then, the inflow to the lower zone (Q_{LZ}) and inflow to groundwater (Q_{GW}) are calculated as follows:

$$Q_{LZ} = F_{LZ}(Q_{PERC} + f) \qquad \textbf{D.1.42}$$

$$Q_{GW} = (1.0 - F_{LZ})(Q_{PERC} + f) \qquad \textbf{D.1.43}$$

Evapotranspiration

PET is used for actual ET simulation. PET is obtained using United States Weather Bureau Class A pan records with an adjustment factor:

$$ET_p = \frac{C_{ET}ET_{classA}}{24} \qquad \textbf{D.1.44}$$

where

ET_p = PER (inches/hr)

ET_{classA} = class A pan measured daily ET (inches/day)

C_{ET} = ET adjustment factor

Actual ET (AET) of interception storage, surface water storage, interflow storage, upper zone storage, and lower zone storage is calculated as a function of individual storages. The sum of AETs from these five storages is the total ATET from the land segment. These AETs are calculated as follows:

- AET in interception storage is computed by the following:

$$AET_{INTCP} = min(ET_p, S_{INTCP}) \quad \textbf{D.1.45}$$
$$S_{INTCP} = S_{INTCP} - AET_{INTCP} \quad \textbf{D.1.46}$$
$$ET_{REM} = ET_p - AET_{INTCP} \quad \textbf{D.1.47}$$

where

AET_{INTCP} = AET from intercetion storage (inches/hr)

ET_{REM} = remaining PET (inches/hr)

- AET in surface detention/runoff storage is computed by the following:

$$\mathrm{AET_{SUR}} = \mathrm{min(ET_{REM}, S_{SUR})} \quad \textbf{D.1.48}$$
$$\mathrm{S_{SUR}} = \mathrm{S_{SUR} - AET_{SUR}} \quad \textbf{D.1.49}$$
$$\mathrm{ET_{REM}} = \mathrm{ET_{REM} - AET_{SUR}} \quad \textbf{D.1.50}$$

where

AET_{SUR} = AET from surface detention/runoff storage (inches/hr)

- AET in interflow storage is computed by the following:

$$AET_{INTFL} = min(ET_{REM}, S_{INTFL}) \quad \textbf{D.1.51}$$
$$S_{INTFL} = S_{INTFL} - AET_{INTFL} \quad \textbf{D.1.52}$$
$$ET_{REM} = ET_{REM} - AET_{INTFL} \quad \textbf{D.1.53}$$

where

AET_{INTFL} = AET from interflow storage (inches/hr)

- AET in upper zone storage is computed by the following:

$$if\ \frac{S_{UZ}}{S_{UZN}} > 2.0$$
$$AET_{UZ} = min(ET_{REM}, S_{UZ}) \quad \textbf{D.1.54}$$
$$if\ \frac{S_{UZ}}{S_{UZN}} \leq 2.0$$
$$AET_{UZ} = min\left(\frac{S_{UZ} ET_{REM}}{2S_{UZN}}, S_{UZ}\right) \quad \textbf{D.1.55}$$
$$S_{UZ} = S_{UZ} - AET_{UZ} \quad \textbf{D.1.56}$$
$$ET_{REM} = ET_{REM} - AET_{UZ} \quad \textbf{D.1.57}$$

where

AET_{UZ} = AET from upper zone storage (inches/hr)

- AET in low zone storage is computed. Vegetation transpiration plays a key role in ET from the lower zone. The factors, such as vegetation type, depth of rooting, density of the vegetation cover, and stage of plant growth along with the moisture content of the soil zone, are associated with ET in the lower zone. All influences from these factors are lumped into the parameter P_{LZET}.

This lower zone ET parameter can differ monthly to reflect temporal variation of vegetation type and growth and seasonal moisture change. The maximum ET opportunity in the lower zone is computed using the lower zone ET parameter based on the lower zone soil moisture content as follows:

$$ET_{LZMAX} = \left(\frac{0.25}{1.0 - P_{LZET}}\right)\left(\frac{S_{UZ}}{S_{UZN}}\right)\left(\frac{T_h}{24.0}\right) \qquad \textbf{D.1.58}$$

where

ET_{LZMAX} = the index to maximum ET opportunity in the lower zone (inches /hr)

P_{LZET} = lower zone ET parameter

The ET ability in the land segment varies between 0 to maximum ET opportunity (ET_{LZMAX}), as shown in **Figure D-1-4**. When remaining PET (ET_{REM}) after upper zone ET is greater than ET_{LZMAX}, the lower zone AET is equal to the entire area under the ET opportunity line. Otherwise, the AET from the lower zone is the grey area in the figure.

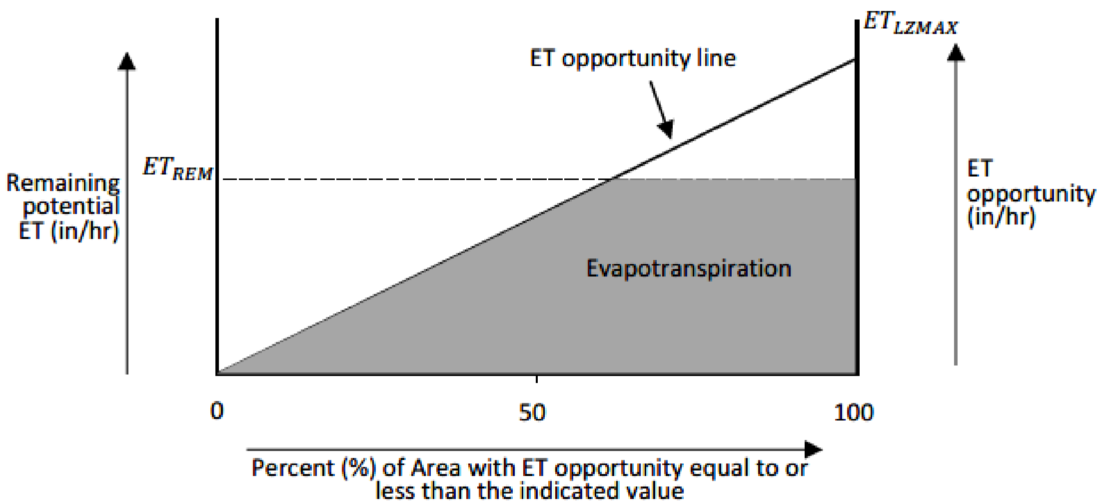

Figure D-1-4. PET and AET from the lower zone.

The equations for calculated AET are as follows:

$if\ ET_{REM} \geq ET_{LZMAX}$

$$AET_{LZ} = 0.5ET_{LZMAX} \qquad \textbf{D.1.59}$$

$if\ ET_{REM} < ET_{LZMAX}$

$$AET_{LZ} = ET_{REM}\left(1.0 - \frac{ET_{REM}}{2ET_{LZMAX}}\right) \qquad \textbf{D.1.60}$$

where

AET_{LZ} = AET from the lower zone (inches/hr)

Using $S_{LZ} - 0.02$ instead of S_{LZ} is to prevent lower zone storage being exhausted by ET. When P_{LZET} is less than 0.5, the calculated AET (AET_{LZ}) is further reduced by multiplying by P_{LZET} by

2. This is designed to account for the land segment devoid of any vegetation that can draw from the lower zone:

$if P_{LZET} < 0.5$

$$AET_{LZ} = 2P_{LZET}AET_{LZ} \quad \textbf{D.1.61}$$

The calculated AET_{LZ} here is further limited by the available lower zone storage. It is assumed that ET will not completely empty storage in the lower zone. A value of 0.02-inch storage is used as the minimum storage in the lower zone, meanwhile the lower zone storage is updated:

$$AET_{LZ} = min(AET_{LZ}, S_{UZ} - 0.02) \quad \textbf{D.1.62}$$

$$S_{LZ} = S_{LZ} - AET_{LZ} \quad \textbf{D.1.63}$$

Thus the total AET is the summation of AETs from these five storages:

$$AET_{TOTAL} = AET_{INTCEP} + AET_{SUR} + AET_{INTFL} + AET_{UZ} + AET_{LZ} \quad \textbf{D.1.64}$$

Modification to Lower Zone Inflow to Improve Groundwater Response

When the groundwater table is high enough to be above the lower zone influence elevation, which is land surface elevation subtracted by lower zone influence depth (**Figure D-1-5**), a portion of the lower zone is occupied by groundwater storage. That means that a portion of lower zone inflow calculated by the original HSPF module actually becomes groundwater storage.

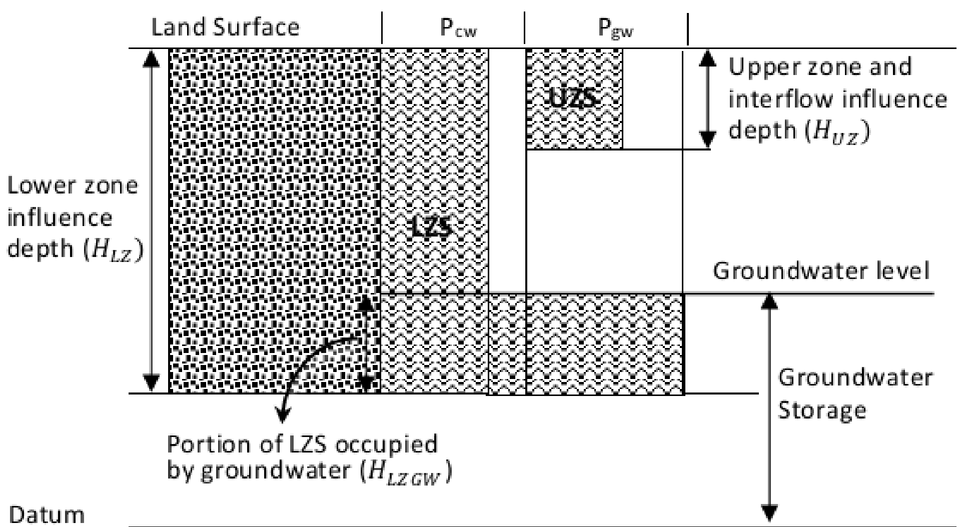

Figure D-1-5. Sketch of soil moisture in the unsaturated zone showing a part of the lower zone storage (LZS) occupied by groundwater storage due to a high groundwater table.

The fraction of this part of water is calculated according to the fraction of the lower zone occupied by groundwater:

$$\alpha_{LZGW} = \frac{H_{LZGW}}{H_{LZ}} \quad \textbf{D.1.65}$$

Then, the lower zone inflow computation **Equation D.1.42** is modified by multiplying by $(1 - \alpha_{LZGW})$:

$$Q_{LZ} = F_{LZ}(Q_{PERC} + f)(1 - \alpha_{LZGW}) \qquad \textbf{D.1.66}$$

The groundwater inflow computation **Equation D.1.43** becomes the following:

$$Q_{GW} = (Q_{PERC} + f) - Q_{LZ} = (Q_{PERC} + f)(1 - F_{LZ}(1 - \alpha_{LZGW})) \qquad \textbf{D.1.67}$$

With this modification of lower zone and groundwater inflow, the groundwater response to infiltration improves significantly. These are compared in **Attachment D-4**.

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ATTACHMENT D-2: MODEL PARAMETERS

Table D-2-1 provides model parameters for each land use type. See **Table D-5** for the descriptions of these parameters. **Table D-2-2** provides the PET monthly coefficients for each land use type.

Table D-2-1. Model parameters for each land use type. [Note: See **Table D-5** for parameter definitions.]

Land Use	CEPSC	UZSN	NSUR	INTFW	IRC	LZETP	LZSN	INFILT	INFILD	INFEXP	AGWETP	CANPMPPARM	PMP_UC	PMP_LC	CAN_CONDUCTANCE
100	0.02	0.3	0.4	0	0.9	0.35	4	0.12	1.5	2	0.1	0.625	4.75	4	0.3
111	0.02	0.3	0.4	0	0.9	0.3	4	0.12	1.5	2	0.1	0.625	5.25	4	0.3
113	0.02	0.3	0.4	0	0.9	0.3	4	0.12	1.5	2	0.1	0.625	4.75	4	0.3
118	0.02	0.3	0.4	0	0.9	0.3	4	0.12	1.5	2	0.1	0.625	5.25	4	0.3
121	0.02	0.3	0.4	0	0.9	0.3	4	0.12	1.5	2	0.1	0.625	5.25	4	0.3
122	0.02	0.3	0.4	0	0.9	0.3	4	0.12	1.5	2	0.1	0.625	5.25	4.5	0.3
129	0.02	0.3	0.4	0	0.9	0.3	4	0.12	1.5	2	0.1	0.625	5.25	4	0.3
131	0.02	0.3	0.4	0	0.9	0.2	4	0.12	1.5	2	0.1	0.625	4.75	4	0.3
132	0.02	0.3	0.4	0	0.9	0.2	4	0.12	1.5	2	0.1	0.625	4.75	4	0.3
133	0.02	0.3	0.4	0	0.9	0.2	4	0.12	1.5	2	0.1	0.625	4.75	4	0.3
134	0.02	0.3	0.4	0	0.9	0.2	4	0.12	1.5	2	0.1	0.625	5.25	4.5	0.3
139	0.02	0.3	0.4	0	0.9	0.2	4	0.12	1.5	2	0.1	0.625	5.25	4	0.3
140	0.02	0.3	0.4	0	0.9	0.35	4	0.12	1.5	2	0.1	0.625	5.25	4.5	0.3
141	0.02	0.3	0.4	0	0.9	0.35	4	0.12	1.5	2	0.1	0.625	4.75	4	0.3
155	0.02	0.3	0.4	0	0.9	0.2	4	0.12	1.5	2	0.1	0.625	5.25	4.5	0.3
163	0.02	0.3	0.4	0	0.9	0.35	4	0.12	1.5	2	0.1	0.625	5.25	4	0.3
166	0.02	0.3	0.4	0	0.9	0.35	4	0.12	1.5	2	0.1	0.625	5.25	4	0.3
170	0.02	0.3	0.4	0	0.9	0.35	4	0.12	1.5	2	0.1	0.625	5.25	4.5	0.3
171	0.02	0.3	0.4	0	0.9	0.35	4	0.12	1.5	2	0.1	0.625	5.25	4.5	0.3
180	0.02	0.3	0.4	0	0.9	0.35	4	0.12	1.5	2	0.1	0.625	5.25	4.5	0.3
182	0.02	0.3	0.4	0	0.9	0.35	4	0.12	1.5	2	0.1	0.625	5.25	4	0.3
190	0.02	0.3	0.4	0	0.9	0.35	4	0.12	1.5	2	0.1	0.6	4.75	4	0.3
192	0.02	0.3	0.4	0	0.9	0.35	4	0.12	1.5	2	0.1	0.5	5.25	4.5	0.3
211	0.02	0.5	0.4	0	0.9	0.5	4	0.21	2	2	0.35	0.08	5	4.1	0.3
212	0.02	0.5	0.4	0	0.9	0.4	4	0.21	2	2	0.35	0.5	4.5	4	0.3
213	0.02	0.5	0.4	0	0.9	0.5	4	0.21	2	2	0.35	0.08	5	4.1	0.3
214	0.02	0.5	0.4	0	0.9	0.5	4	0.21	2	2	0.35	0.08	5	4.1	0.3
215	0.02	0.5	0.4	0	0.9	0.5	4	0.21	2	2	0.35	0.1	5	4	0.3

Table D-2-1. Continued.

Land Use	CEPSC	UZSN	NSUR	INTFW	IRC	LZETP	LZSN	INFILT	INFILD	INFEXP	AGWETP	CANPMPPARM	PMP_UC	PMP_LC	CAN_CONDUCTANCE
221	0.02	0.5	0.4	0	0.9	0.4	4	0.21	2	2	0.35	0.5	4.5	4	0.3
261	0.02	0.5	0.4	0	0.9	0.5	4	0.21	2	2	0.35	0.5	4.5	4	0.3
310	0.02	0.5	0.4	0	0.9	0.4	4	0.21	2	2	0.35	0.1	4.5	4	0.3
320	0.02	0.5	0.4	0	0.9	0.4	4	0.21	2	2	0.35	0.1	4.5	4	0.3
321	0.02	0.5	0.4	0	0.9	0.4	4	0.21	2	2	0.35	0.35	4	3.5	0.3
330	0.02	0.5	0.4	0	0.9	0.4	4	0.21	2	2	0.35	0.1	4.5	4	0.3
411	0.02	0.5	0.4	0	0.9	0.7	4	0.21	2	2	0.35	0.1	4.5	4	0.3
420	0.02	0.5	0.4	0	0.9	0.7	4	0.21	2	2	0.35	0.1	4.5	4	0.3
422	0.02	0.5	0.4	0	0.9	0.7	4	0.21	2	2	0.35	0.1	4.5	4	0.3
440	0.02	0.5	0.4	0	0.9	0.7	4	0.21	2	2	0.35	0.08	5	4.1	0.3
511	0.02	0.4	0.4	0	0.9	0.24	4	0	2	2	0.65	4	0	0	0.3
525	0.02	0.4	0.4	0	0.9	0.24	4	0	2	2	0.65	4	0	0	0.3
530	0.02	0.4	0.4	0	0.9	0.24	4	0	2	2	0.65	4	5.25	4.5	0.3
541	0.02	0.4	0.4	0	0.9	0.24	4	0	2	2	0.65	4	0	0	0.3
600	0.02	0.4	0.4	0	0.9	0.65	4	0.05	2	2	0.65	0.15	4	3.5	0.3
610	0.02	0.4	0.4	0	0.9	0.65	4	0.05	2	2	0.65	0.2	5.25	4.5	0.3
612	0.02	0.4	0.4	0	0.9	0.65	4	0.05	2	2	0.65	0.2	5.25	4.5	0.3
617	0.02	0.4	0.4	0	0.9	0.65	4	0.05	2	2	0.65	0.1	5	4	0.3
620	0.02	0.4	0.4	0	0.9	0.65	4	0.05	2	2	0.65	0.08	5	4.1	0.3
621	0.02	0.4	0.4	0	0.9	0.65	4	0.05	2	2	0.65	0.08	5	4.1	0.3
624	0.02	0.4	0.4	0	0.9	0.65	4	0.05	2	2	0.65	0.15	4	3.5	0.3
625	0.02	0.4	0.4	0	0.9	0.65	4	0.05	2	2	0.65	0.15	4	3.5	0.3
641	0.02	0.4	0.4	0	0.9	0.65	4	0.05	2	2	0.65	0.15	4	3.5	0.3
643	0.02	0.4	0.4	0	0.9	0.65	4	0.05	2	2	0.65	0.15	4	3.5	0.3
740	0.02	0.05	0.4	0	0.9	0.5	4	0.06	2	2	0.35	0.625	5.25	4	0.3
811	0.02	0.14	0.4	0	0.9	0.5	4	0.06	2	2	0.35	0.625	5.25	4.5	0.3
814	0.02	0.14	0.4	0	0.9	0.5	4	0.06	2	2	0.35	0.625	4.75	3.5	0.3
831	0.02	0.14	0.4	0	0.9	0.5	4	0.06	2	2	0.35	0.625	5.25	4	0.3

Table D-2-2. PET monthly coefficient per land use type.

Land Use	PET Monthly Coefficient											
	January	February	March	April	May	June	July	August	September	October	November	December
100	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
111	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
113	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
118	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
121	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
122	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
129	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
131	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
132	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
133	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
134	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
139	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
140	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
141	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
155	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
163	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
166	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
170	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
171	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
180	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
182	0.68	0.68	0.68	0.68	0.86	0.95	0.97	1.20	1.20	0.85	0.70	0.68
190	0.65	0.69	0.73	0.82	0.82	0.82	0.95	0.95	0.95	0.72	0.65	0.65
192	0.65	0.69	0.73	0.82	0.82	0.82	0.95	0.95	0.95	0.72	0.65	0.65
211	0.67	0.78	0.87	0.95	1.02	0.97	1.05	1.15	1.10	0.88	0.72	0.66
212	0.67	0.78	0.87	0.95	1.02	0.97	1.05	1.15	1.10	0.88	0.72	0.66
213	0.67	0.78	0.87	0.95	1.02	0.97	1.05	1.15	1.10	0.88	0.72	0.66
214	0.67	0.78	0.87	0.95	1.02	0.97	1.05	1.15	1.10	0.88	0.72	0.66
215	0.67	0.78	0.87	0.95	1.02	0.97	1.05	1.15	1.10	0.88	0.72	0.66
221	0.67	0.78	0.87	0.95	1.02	0.97	1.05	1.15	1.10	0.88	0.72	0.66
261	0.67	0.78	0.87	0.95	1.02	0.97	1.05	1.15	1.10	0.88	0.72	0.66
310	0.62	0.74	0.77	0.88	0.94	0.95	0.95	0.98	0.98	0.81	0.66	0.61
320	0.62	0.74	0.77	0.88	0.94	0.95	0.95	0.98	0.98	0.81	0.66	0.61
321	0.62	0.74	0.77	0.88	0.94	0.95	0.95	0.98	0.98	0.81	0.66	0.61
330	0.62	0.74	0.77	0.88	0.94	0.95	0.95	0.98	0.98	0.81	0.66	0.61
411	0.67	0.80	0.87	0.95	1.02	1.05	1.05	1.15	1.15	0.88	0.72	0.66
420	0.67	0.80	0.87	0.95	1.02	1.05	1.05	1.15	1.15	0.88	0.72	0.66

Table D-2-2. Continued.

Land Use	Potential Evaporation Monthly Coefficient											
	January	February	March	April	May	June	July	August	September	October	November	December
422	0.67	0.80	0.87	0.95	1.02	1.05	1.05	1.15	1.15	0.88	0.72	0.66
440	0.67	0.80	0.87	0.95	1.02	1.05	1.05	1.15	1.15	0.88	0.72	0.66
511	0.58	0.70	0.77	0.84	0.90	0.84	0.87	0.88	0.84	0.74	0.61	0.54
525	0.58	0.70	0.77	0.84	0.90	0.84	0.87	0.88	0.84	0.74	0.61	0.54
530	0.58	0.70	0.77	0.84	0.90	0.84	0.87	0.88	0.84	0.74	0.61	0.54
541	0.58	0.70	0.77	0.84	0.90	0.84	0.87	0.88	0.84	0.74	0.61	0.54
600	0.73	0.82	0.90	0.98	1.05	1.00	1.10	1.15	1.10	0.91	0.74	0.68
610	0.73	0.82	0.90	0.98	1.05	1.00	1.10	1.15	1.10	0.91	0.74	0.68
612	0.73	0.82	0.90	0.98	1.05	1.00	1.10	1.15	1.10	0.91	0.74	0.68
617	0.73	0.82	0.90	0.98	1.05	1.00	1.10	1.15	1.10	0.91	0.74	0.68
620	0.73	0.82	0.90	0.98	1.05	1.00	1.10	1.15	1.10	0.91	0.74	0.68
621	0.73	0.82	0.90	0.98	1.05	1.00	1.10	1.15	1.10	0.91	0.74	0.68
624	0.73	0.82	0.90	0.98	1.05	1.00	1.10	1.15	1.10	0.91	0.74	0.68
625	0.73	0.82	0.90	0.98	1.05	1.00	1.10	1.15	1.10	0.91	0.74	0.68
641	0.73	0.82	0.90	0.98	1.05	1.00	1.10	1.15	1.10	0.91	0.74	0.68
643	0.73	0.82	0.90	0.98	1.05	1.00	1.10	1.15	1.10	0.91	0.74	0.68
740	0.58	0.70	0.77	0.84	0.90	0.84	0.87	0.88	0.84	0.74	0.61	0.54
811	0.65	0.70	0.77	0.84	0.90	0.84	0.95	1.00	1.00	0.74	0.65	0.65
814	0.67	0.72	0.77	0.84	0.92	0.98	1.01	1.07	1.07	0.81	0.67	0.67
831	0.65	0.70	0.77	0.84	0.90	0.84	0.95	1.00	1.00	0.74	0.65	0.65

ATTACHMENT D-3: SURFACE WATER FLOW COMPARISON PLOTS

Figures D-3-1 through **D-3-8** show the comparison plots between the actual and simulated flows from various surface waterbodies within the CRE MFL Watershed. **Figures D-3-9** and **D-3-10** show comparison of calibrated discharges.

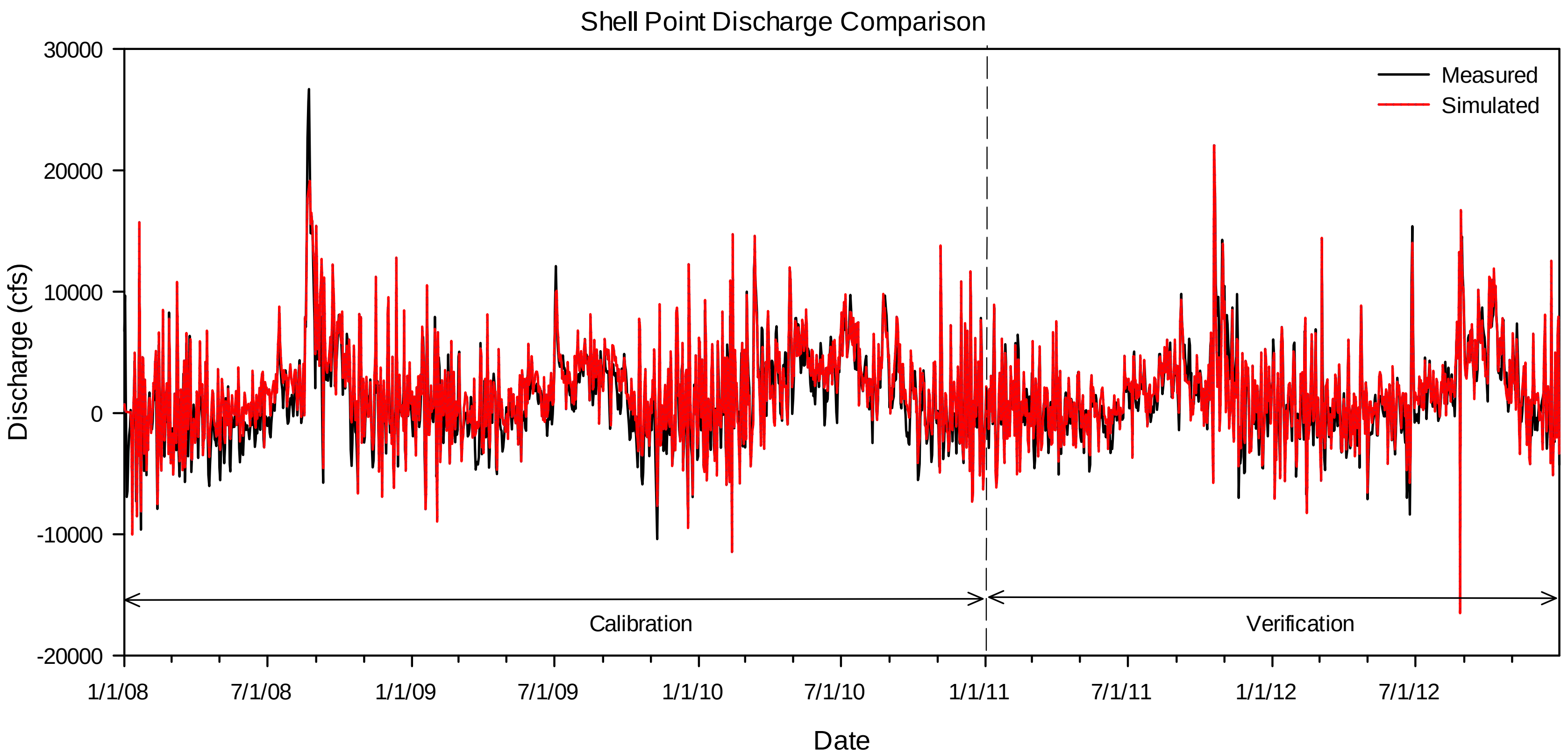

Figure D-3-1. Shell Point discharge comparison plot.

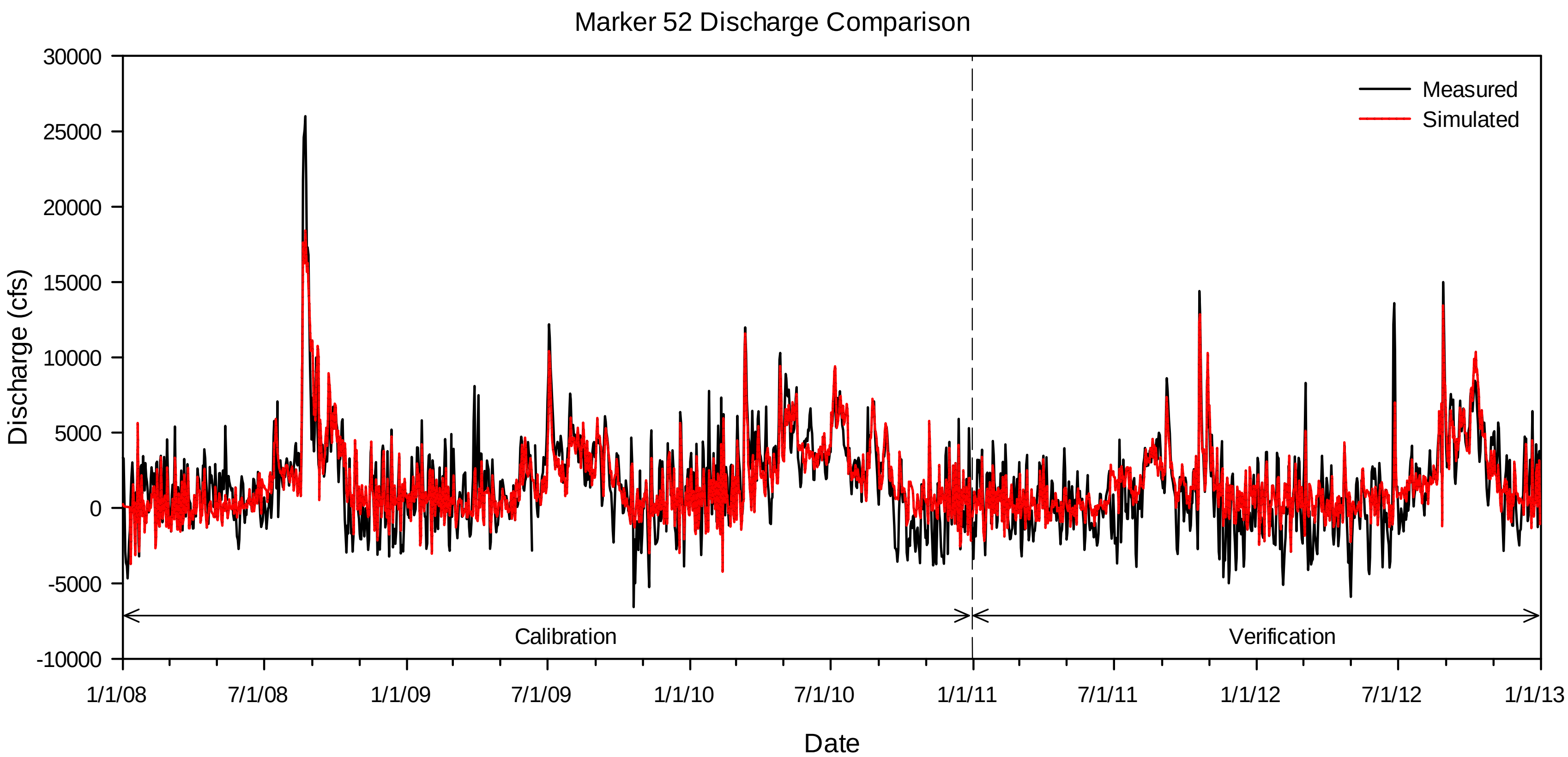

Figure D-3-2. Marker 52 discharge comparison plot.

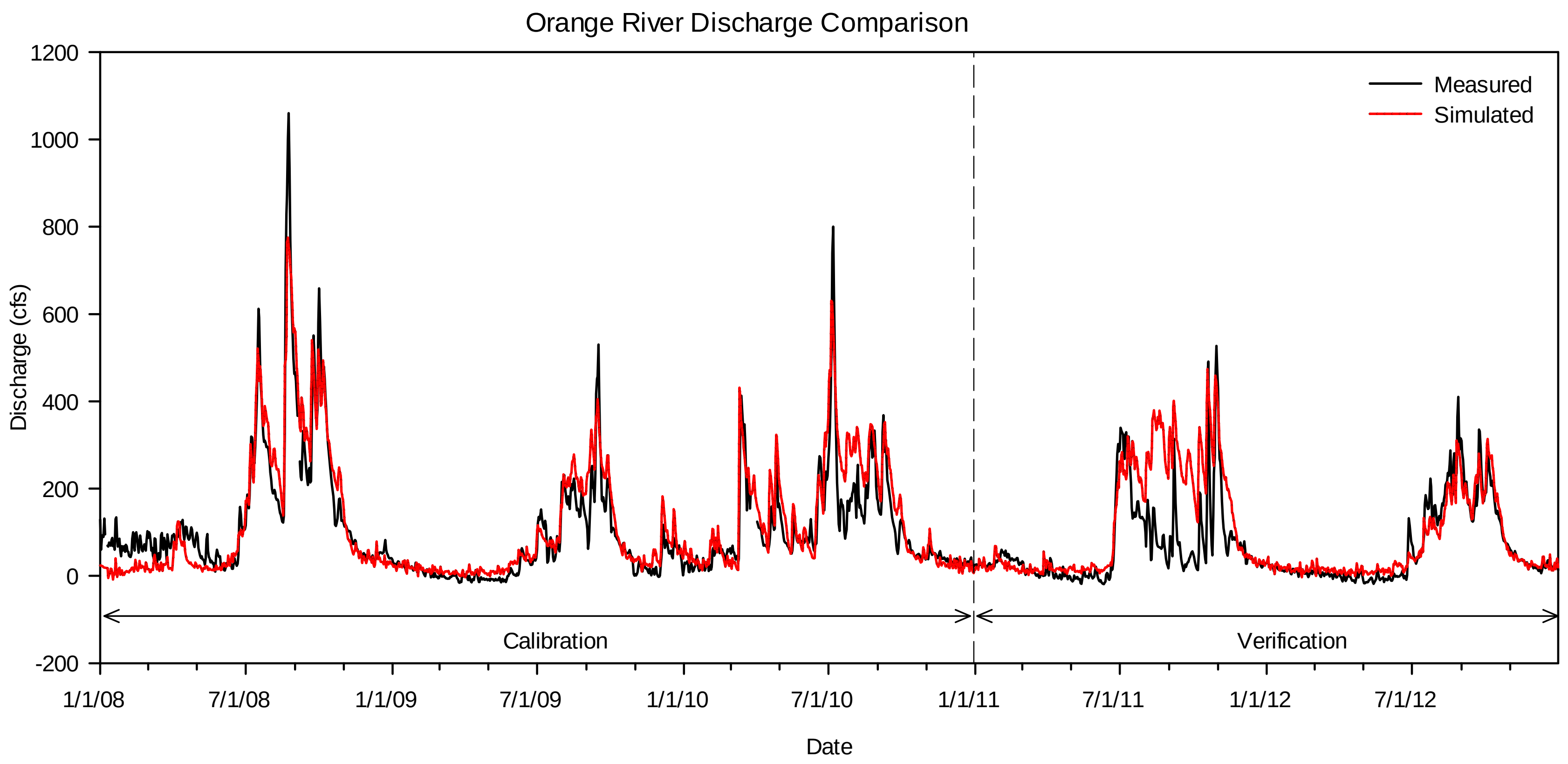

Figure D-3-3. Orange River discharge comparison plot.

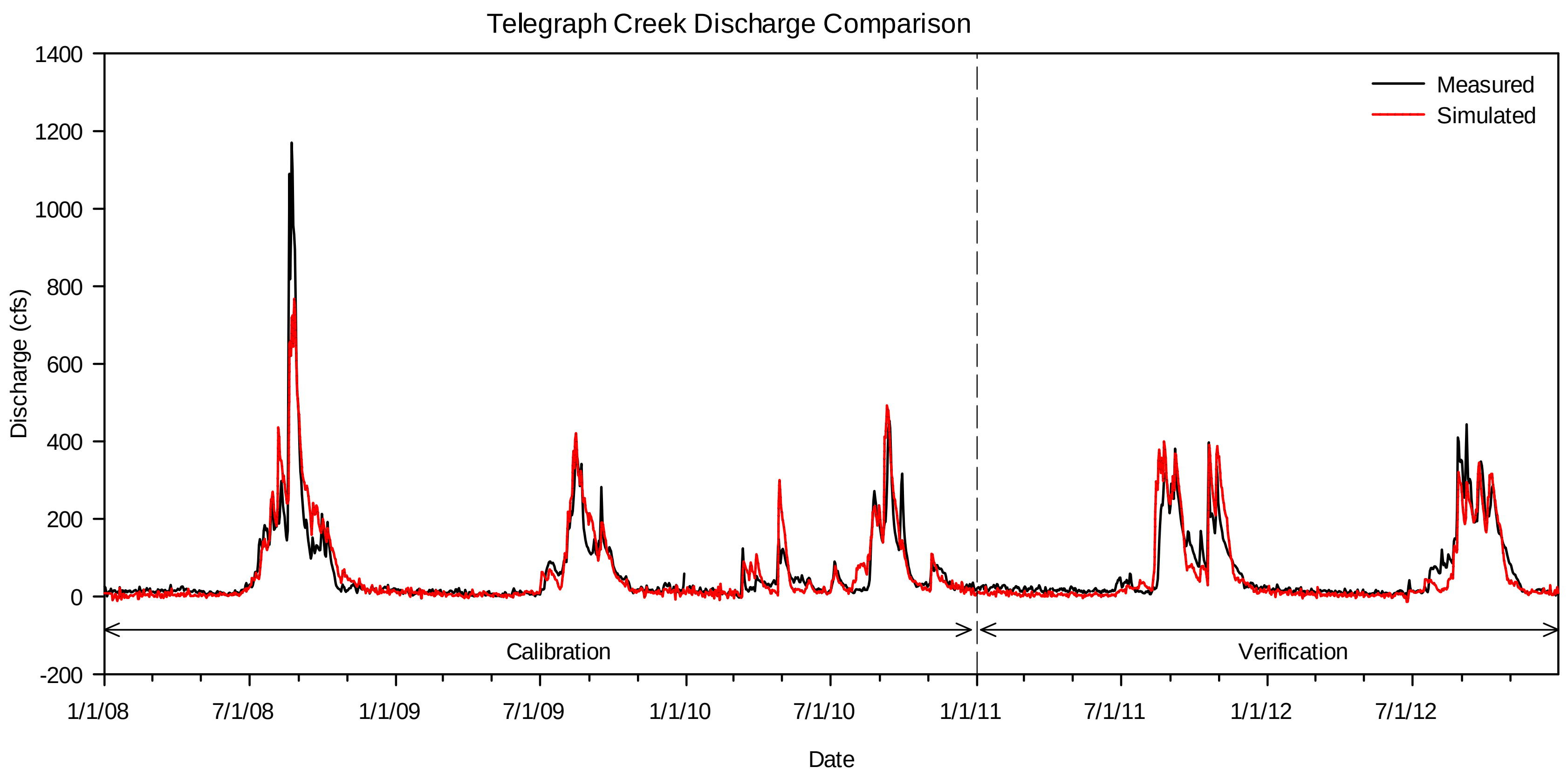

Figure D-3-4. Telegraph Creek discharge comparison plot.

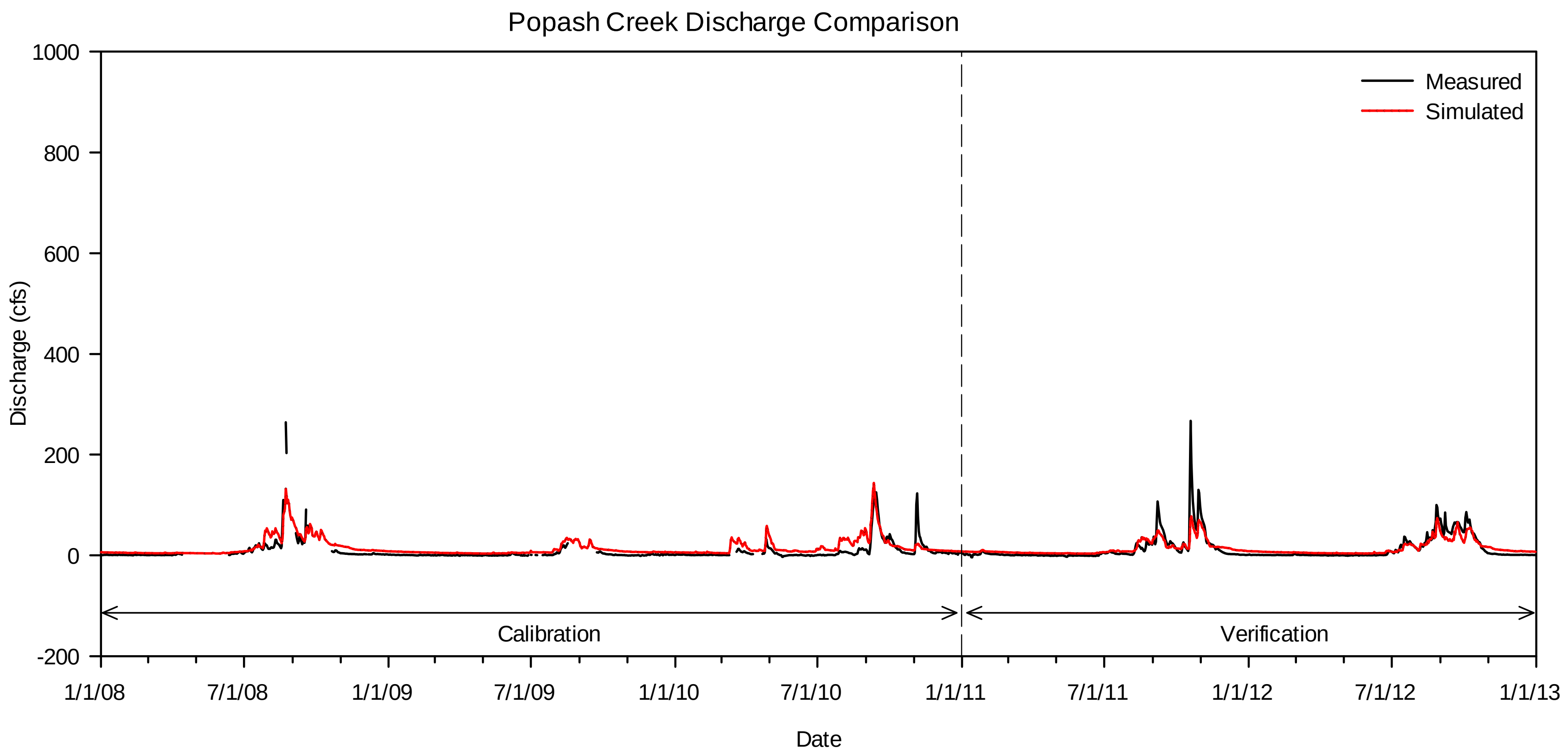

Figure D-3-5. Popash Creek discharge comparison plot.

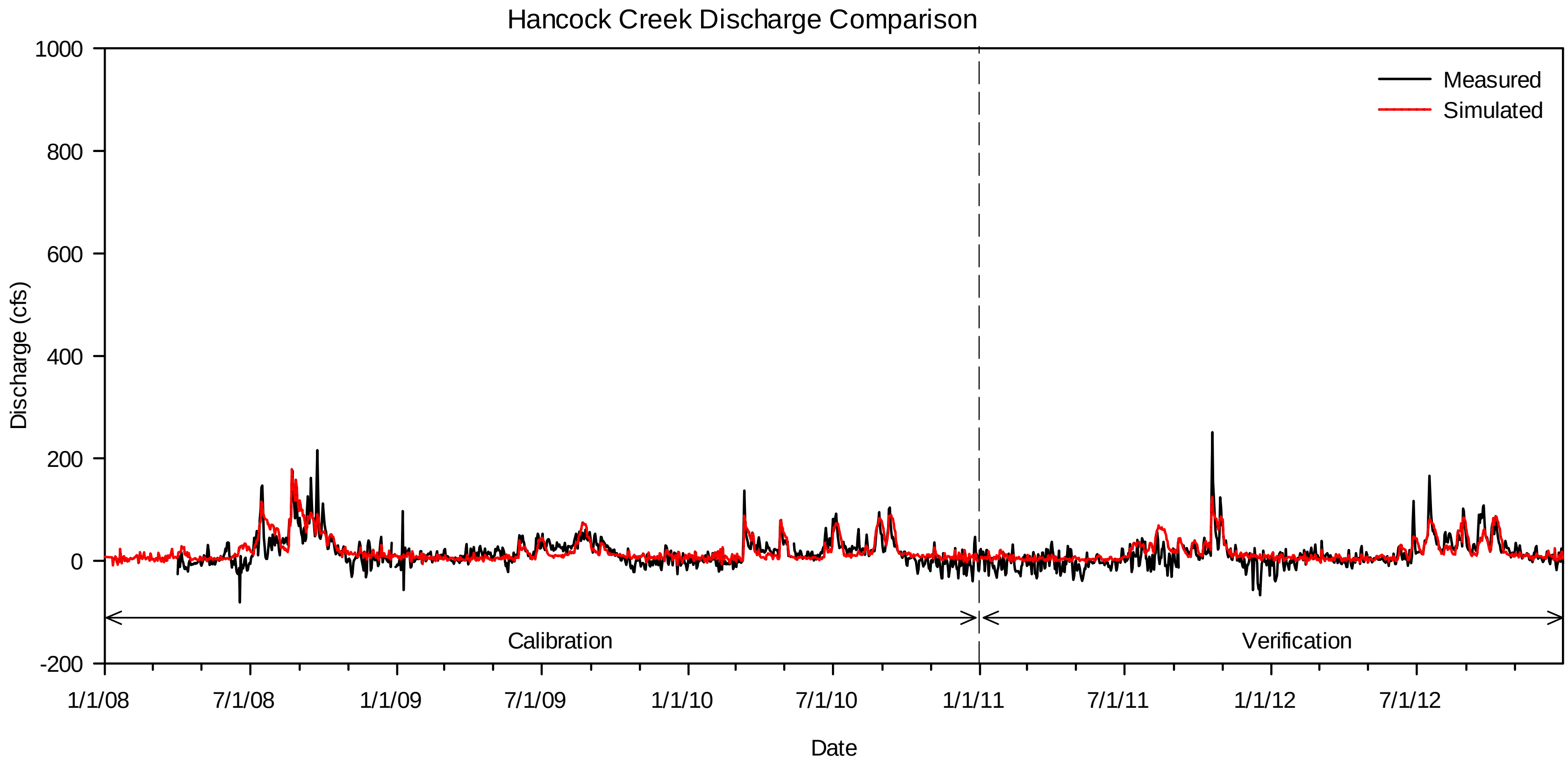

Figure D-3-6. Hancock Creek discharge comparison plot.

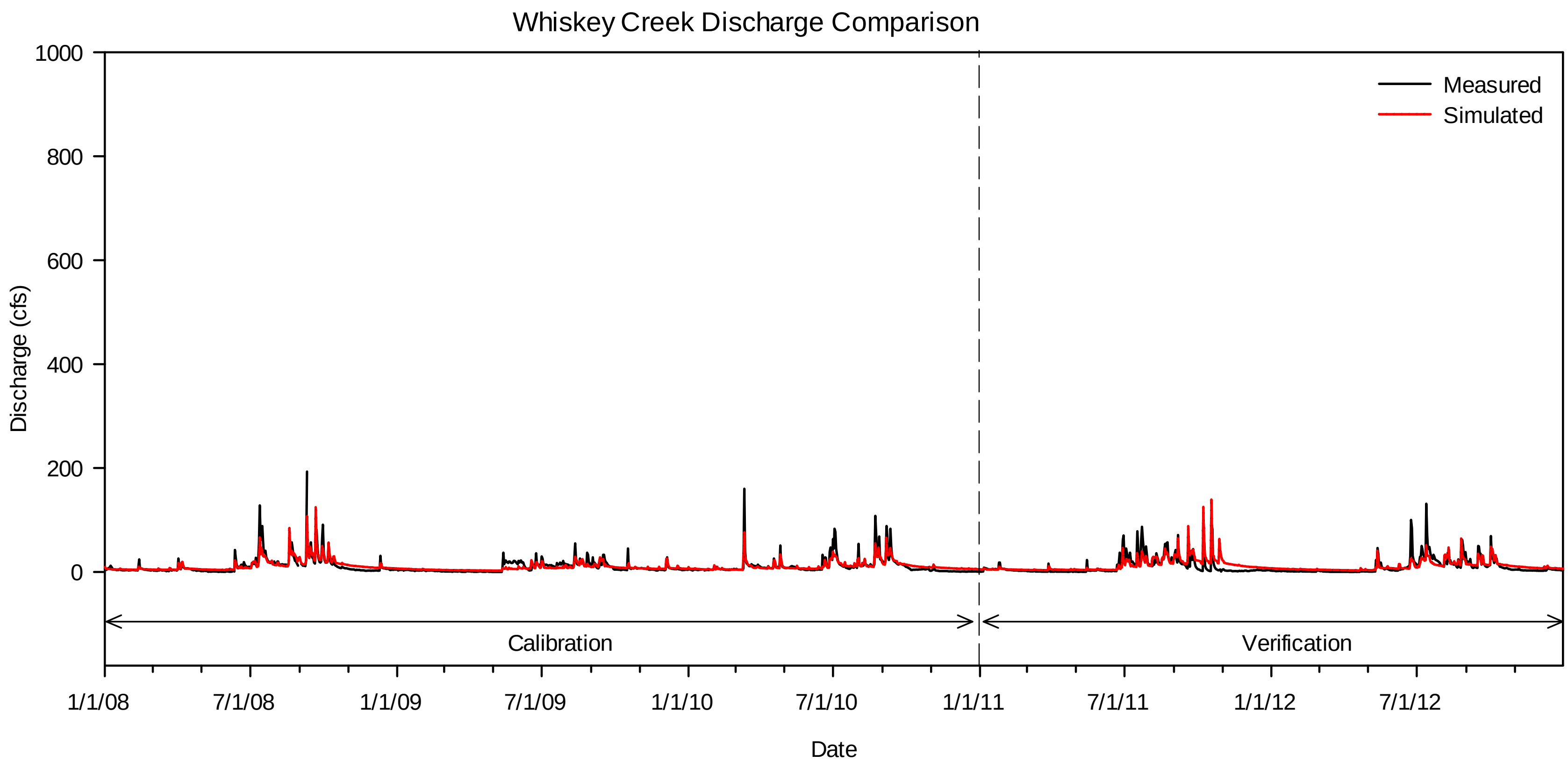

Figure D-3-7. Whiskey Creek discharge comparison plot.

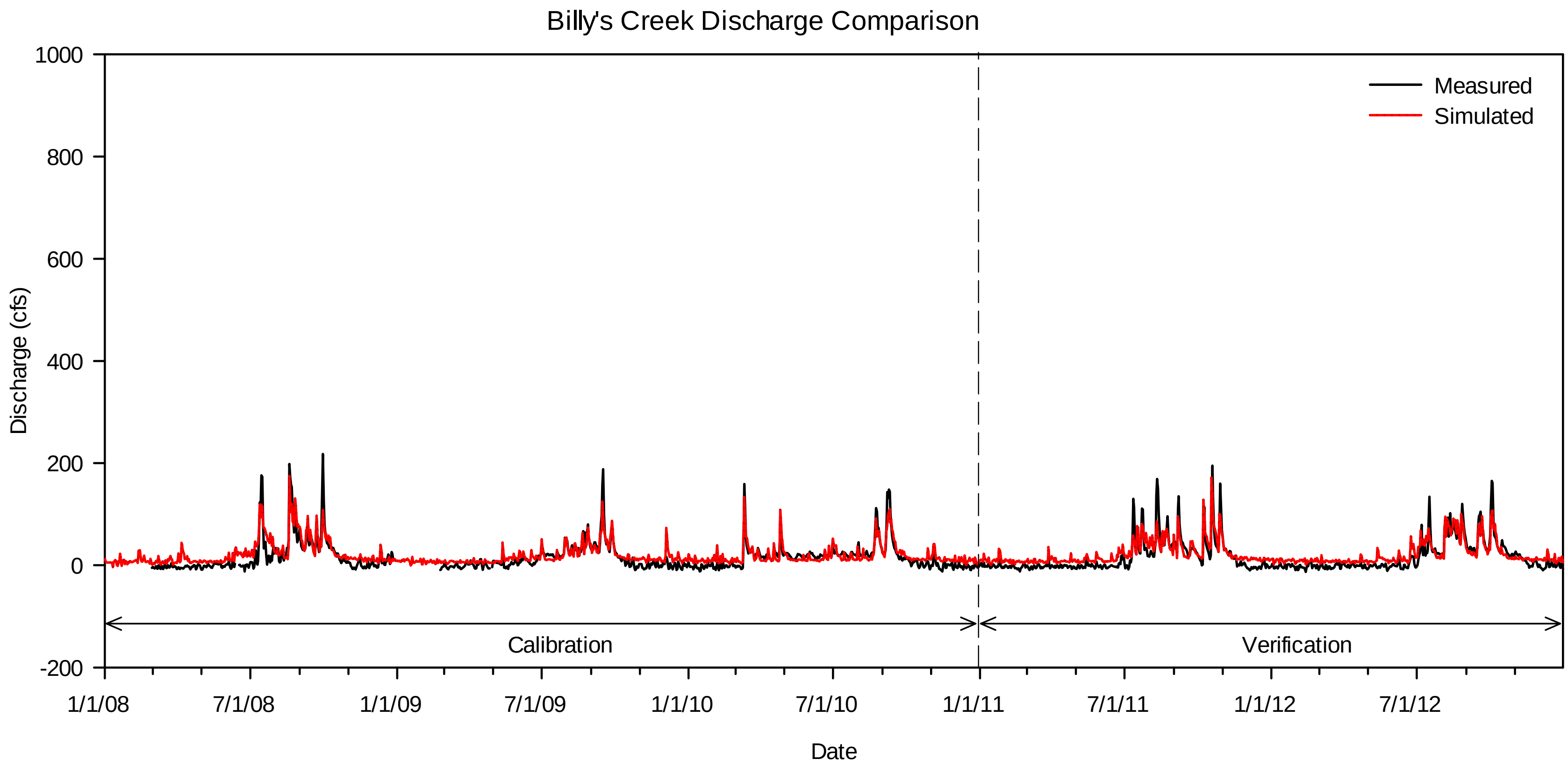

Figure D-3-8. Billy's Creek discharge comparison plot.

Figure D-3-9. Comparison plots of obaccumulative discharge (calibration).

Figure D-3-10. Comparison plots of obaccumulative discharge (verification).

ATTACHMENT D-4: GROUNDWATER STAGE COMPARISON PLOTS

Figures D-4-1 through **D-4-6** compare actual groundwater stages with simulated stages. Units for the plots are ft NAVD88.

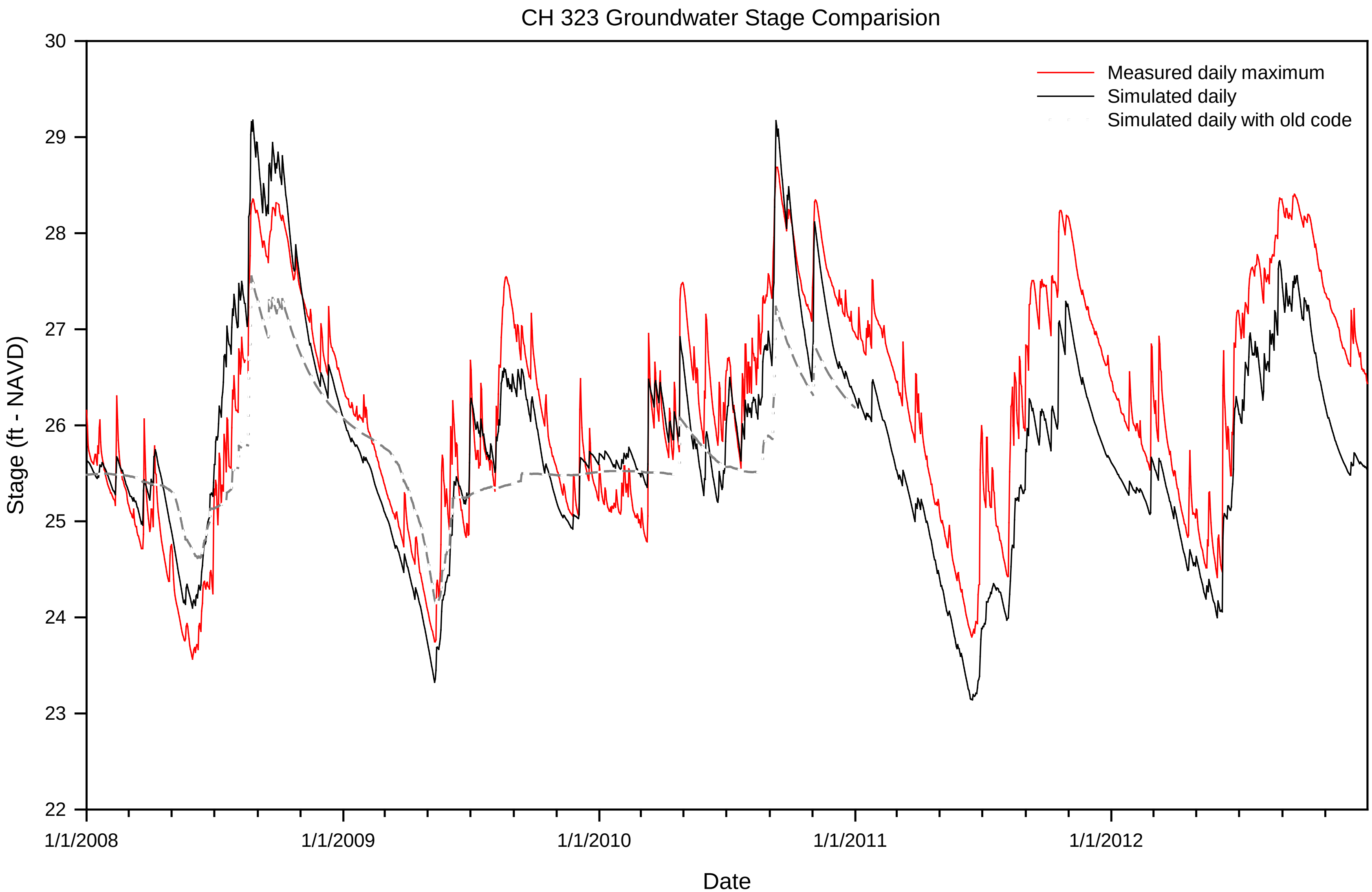

Figure D-4-1. CH323 groundwater stage comparison plot.

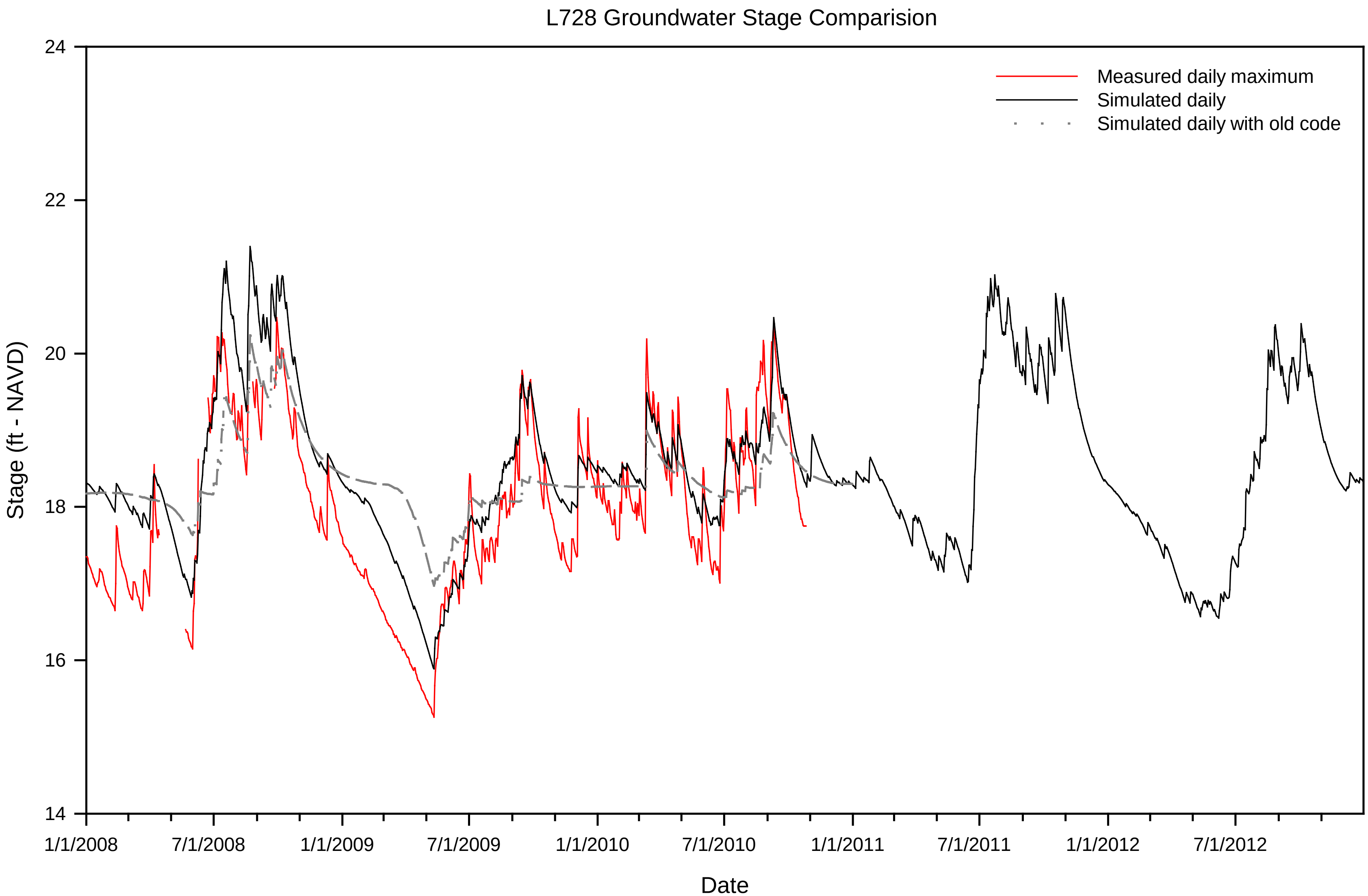

Figure D-4-2. L728 groundwater stage comparison plot.

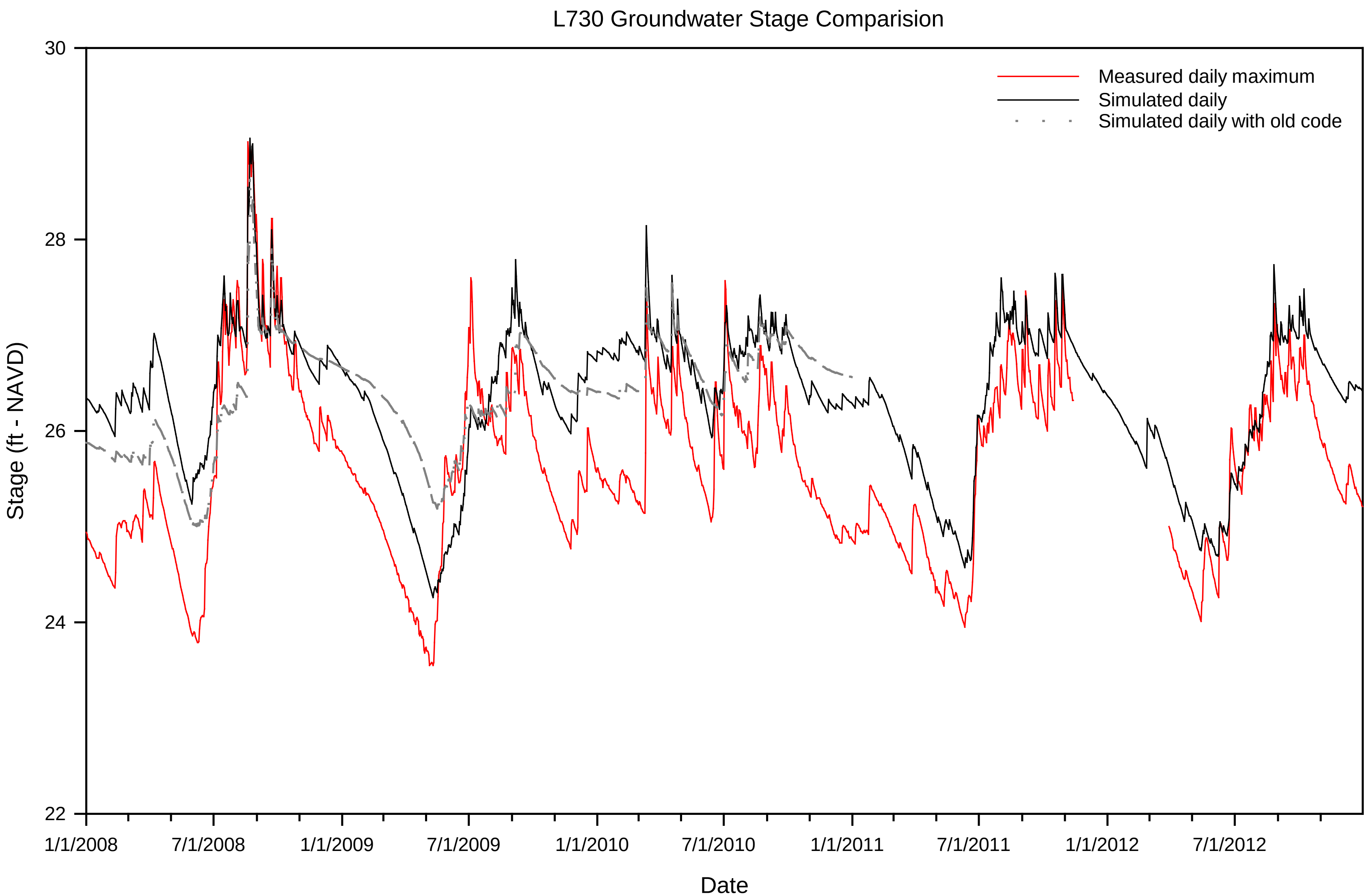

Figure D-4-3. L370 groundwater stage comparison plot.

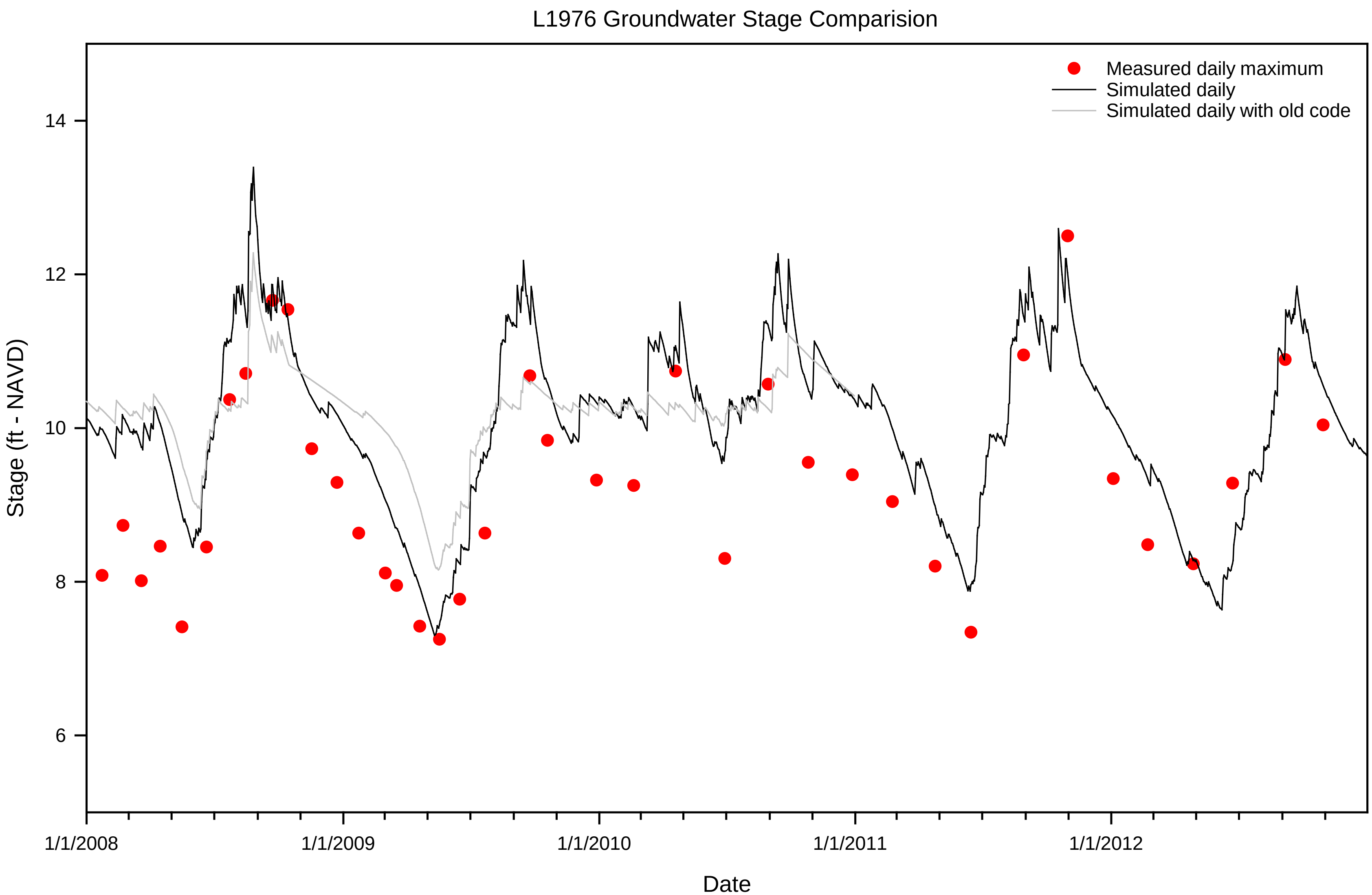

Figure D-4-4. L1976 groundwater stage comparison plot.

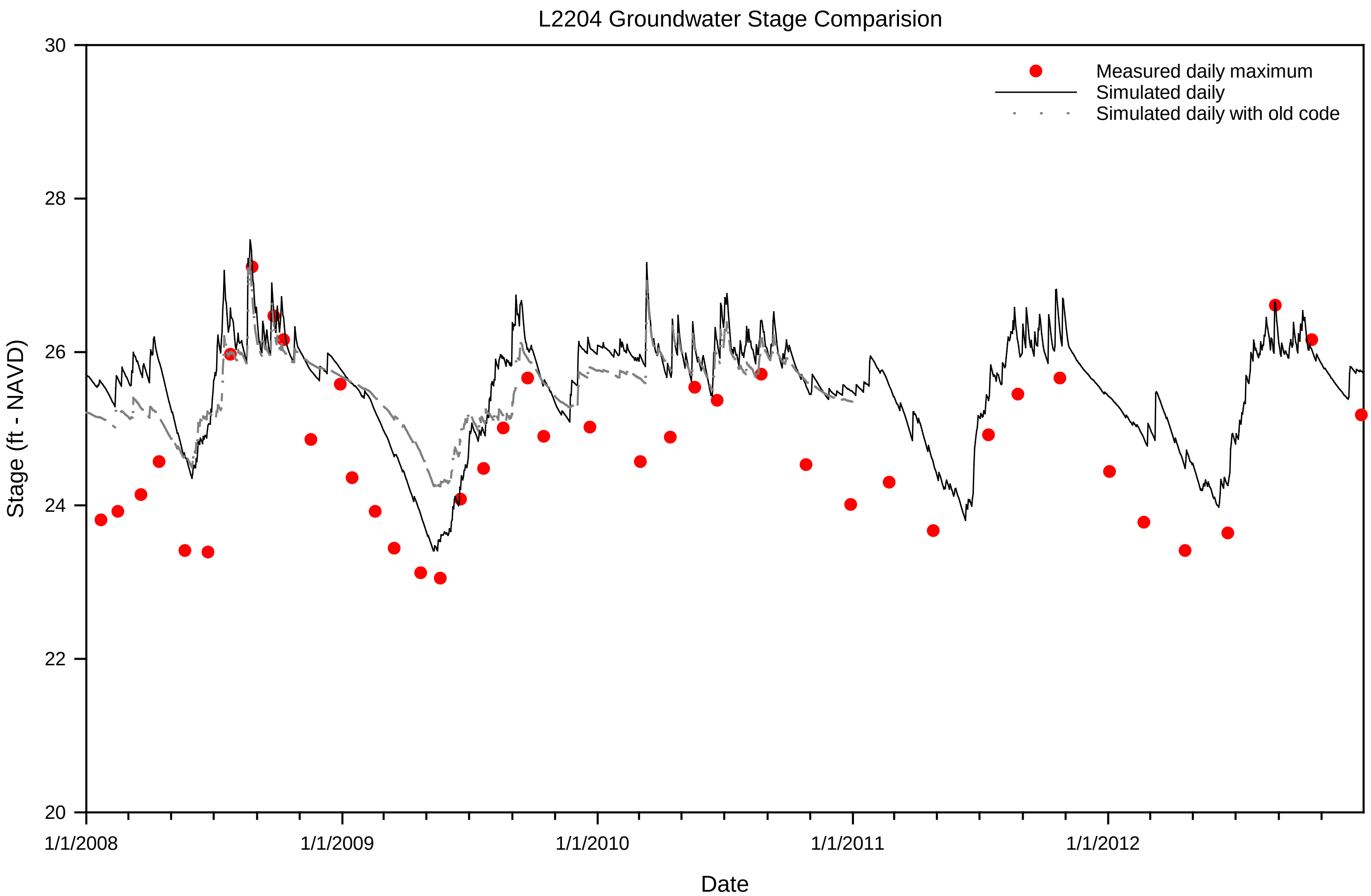

Figure D-4-5. L2204 groundwater stage comparison plot.

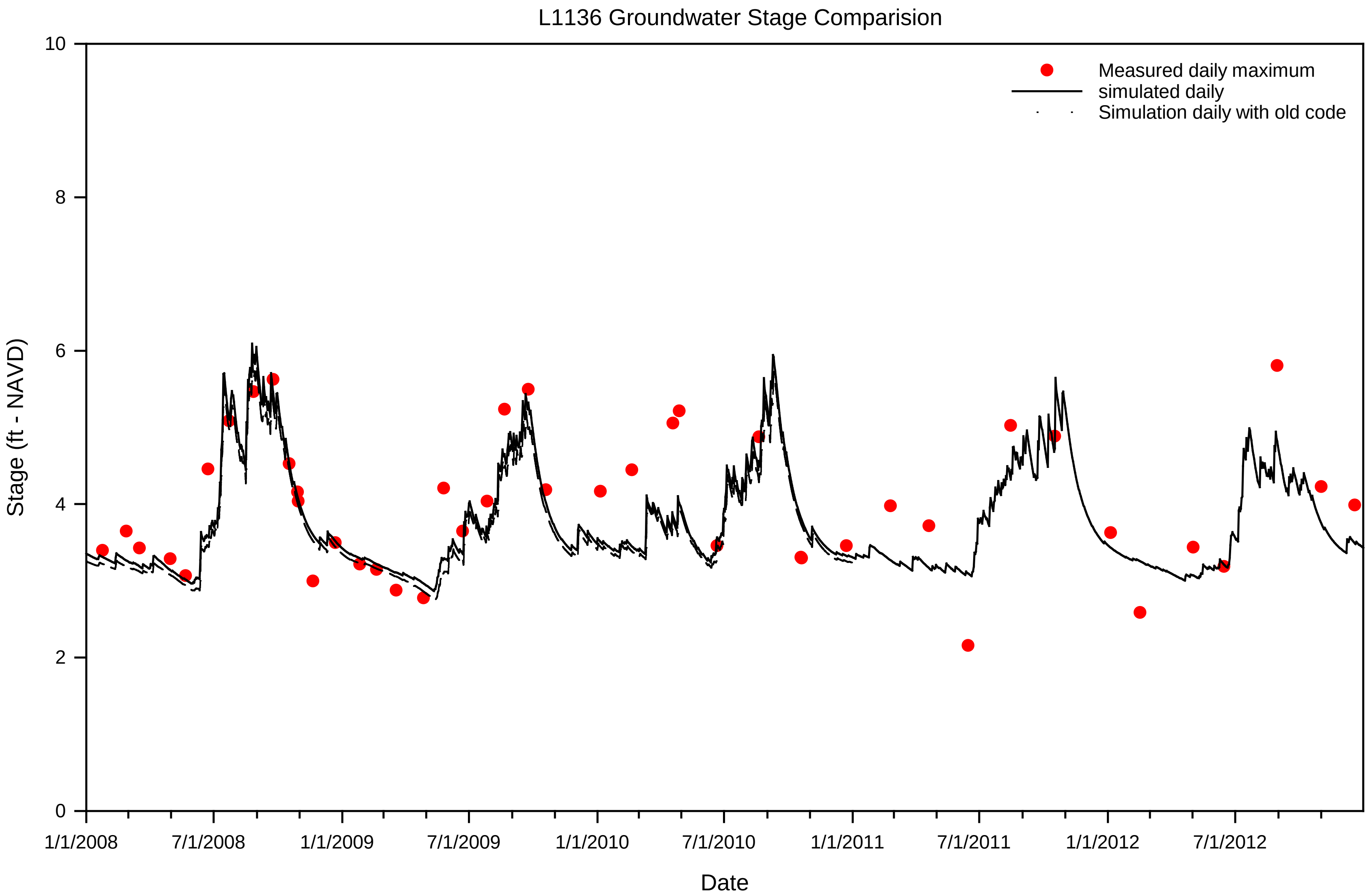

Figure D-4-6. L1136 groundwater stage comparison plot.

ATTACHMENT D-5: GROUNDWATER STAGE AND RIVER STAGE FROM JUNE 2011 TO MAY 2012 ALONG THREE SELECTED TRANSECTS (LOWER, MIDDLE, AND UPPER ESTUARY)

Figures D-5-1 through **D-5-4** provide groundwater profiles and river stages for three selected transects within the CRE. Units for the plots are ft NAVD88.

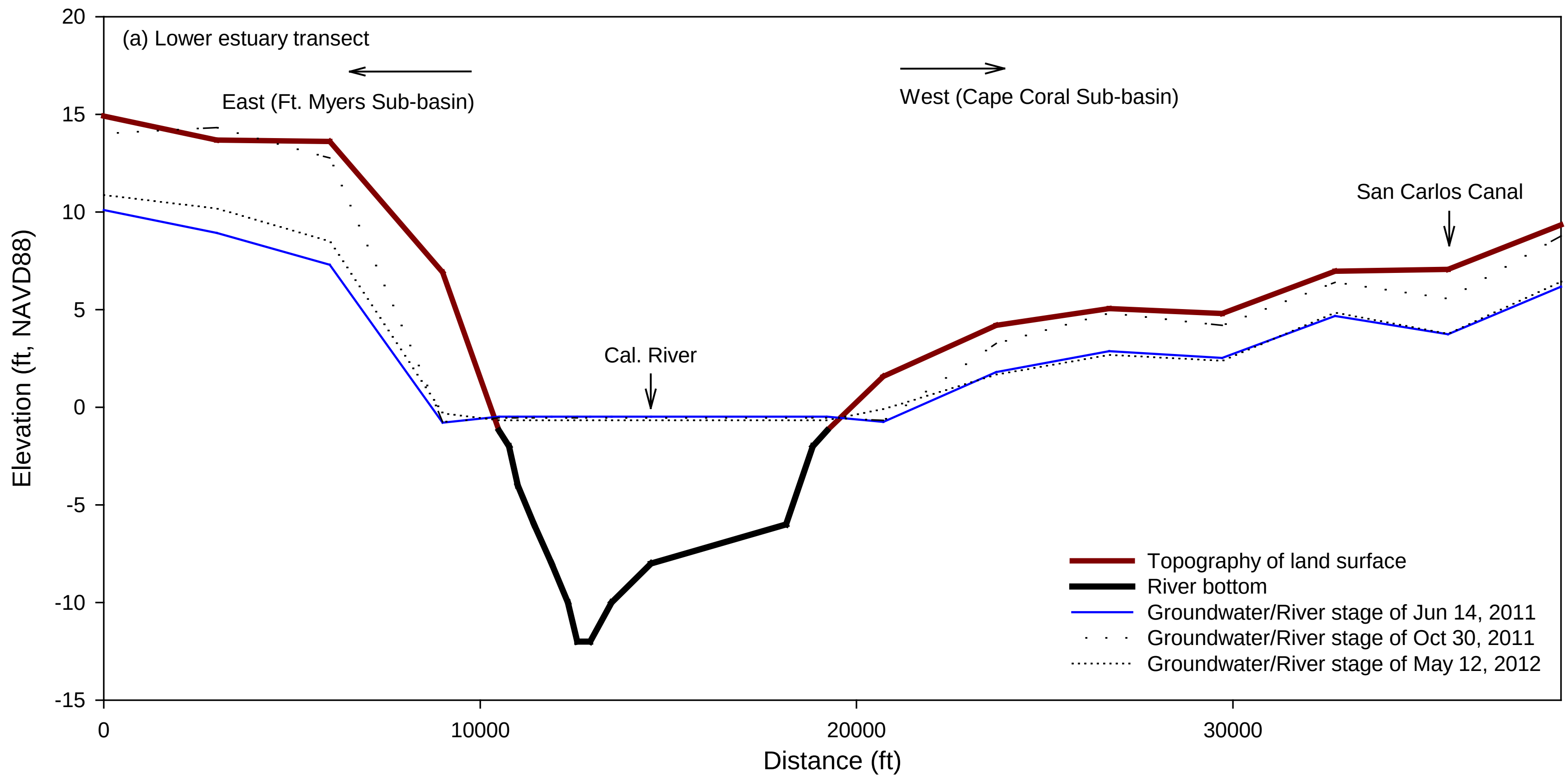

Figure D-5-1. Groundwater profile along *Transect A-A'* in the lower estuary.

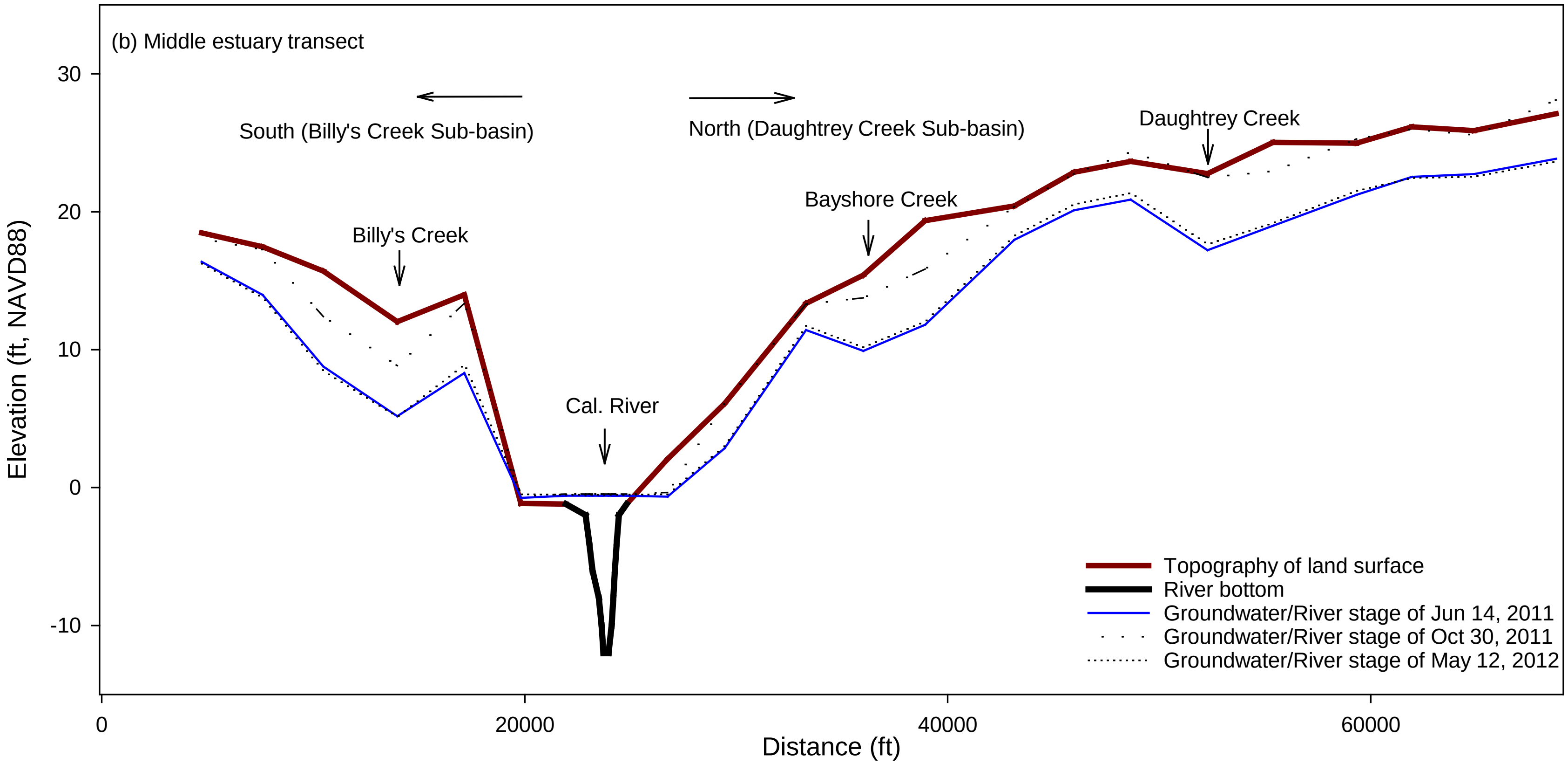

Figure D-5-2. Groundwater profile along *Transect B-B'* in the middle estuary.

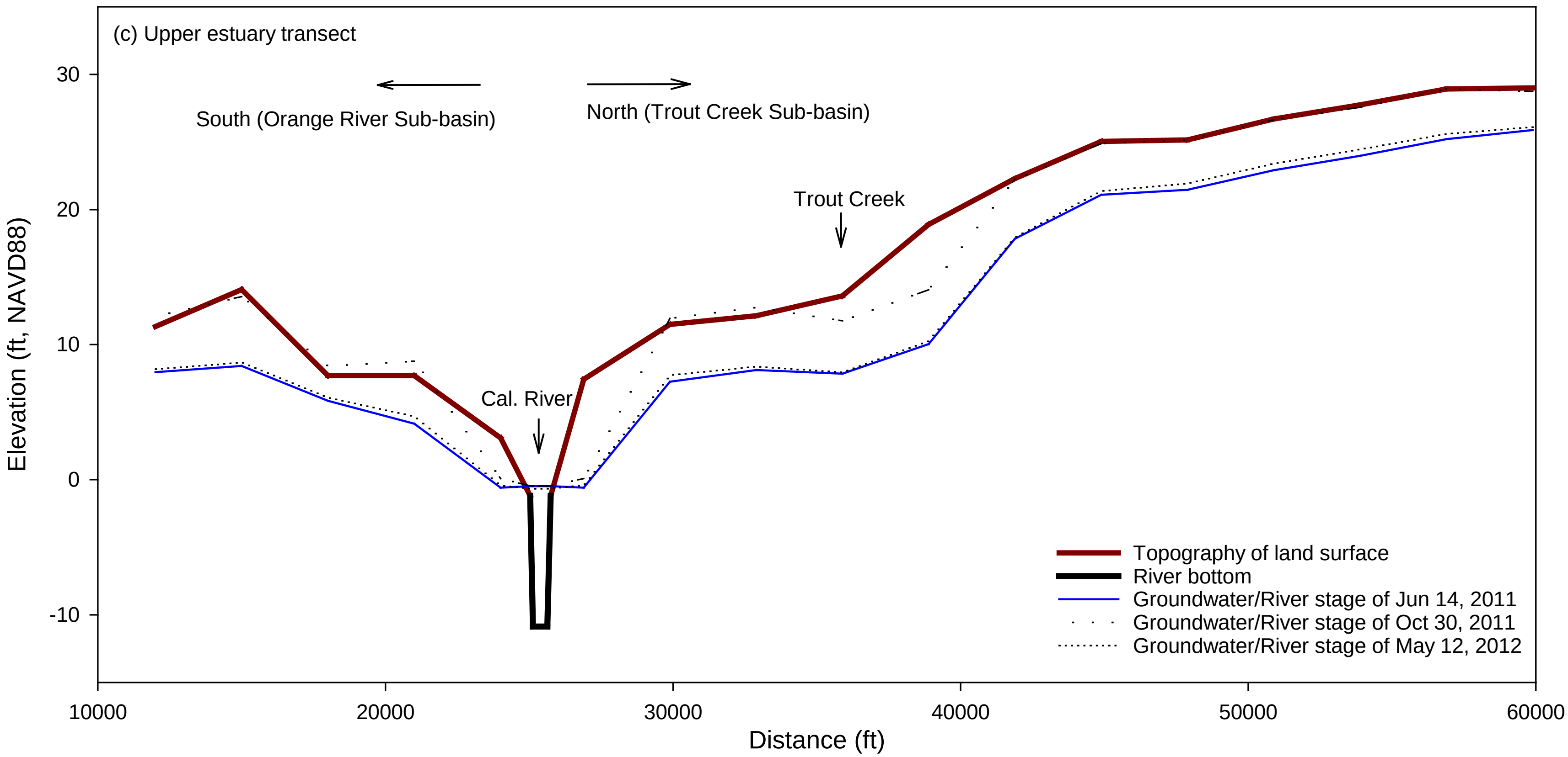

Figure D-5-3. Groundwater profile along *Transect C-C'* in the upper estuary.

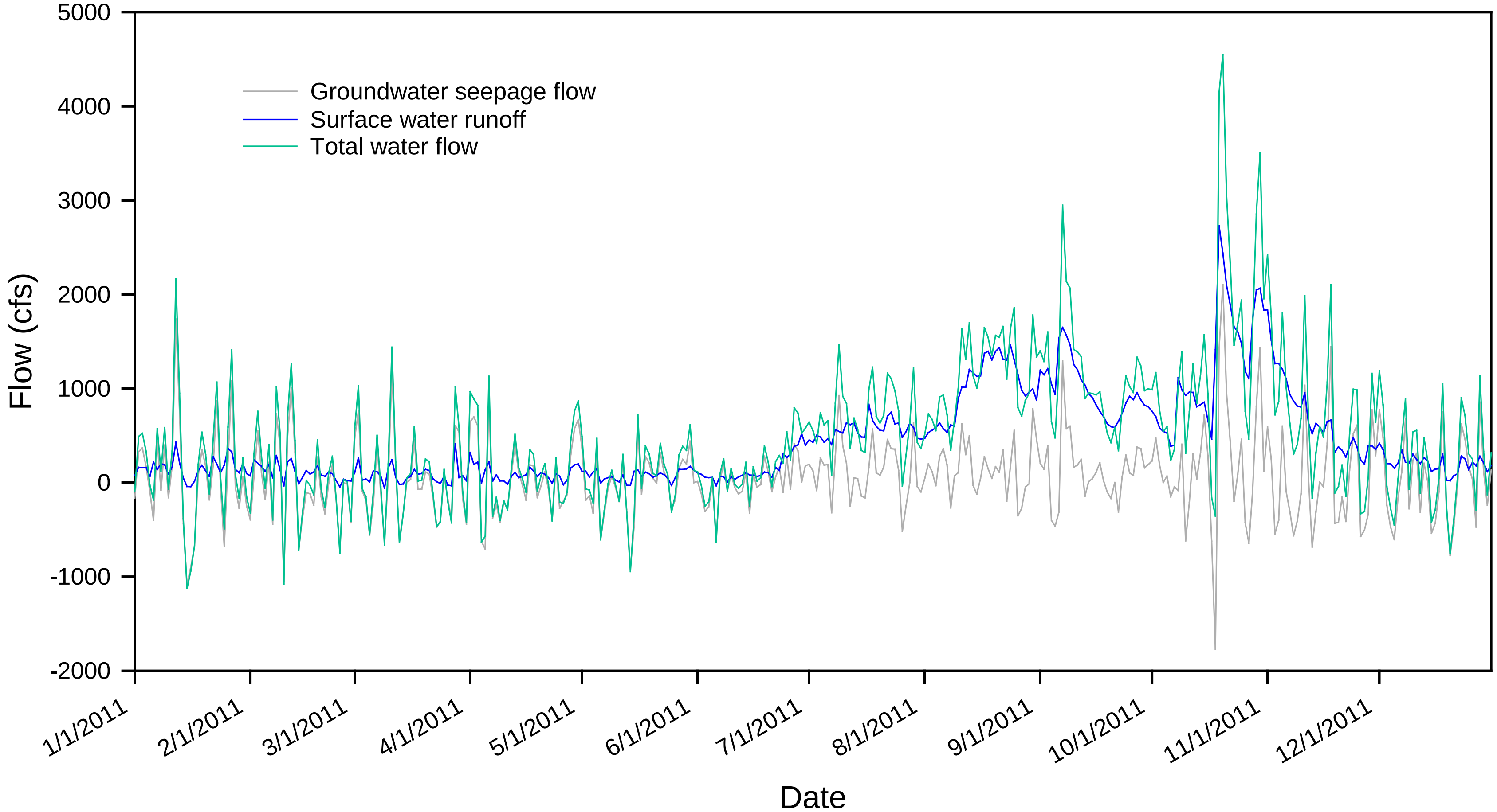

Figure D-5-4. Groundwater seepage flow, surface water runoff, and total water flow to CRE in 2011.