RECOVER Northern Estuaries Performance Measures: Salinity Envelope and Hydrologic Criteria

Date Revised: April 2020
Acceptance Status: TBD
Type of Performance Measure: Evaluation

ABSTRACT

The purpose of the Northern Estuaries Salinity Envelope Performance Measure (PM) is to provide biologically- and ecologically-driven metrics for evaluation and assessment of salinity regimes that sustain healthy ecosystems of the Northern Estuaries, which include the St. Lucie Estuary (SLE), Southern Indian River Lagoon (S-IRL), Loxahatchee River Estuary (LRE), and the Caloosahatchee River Estuary (CRE) in the northern Everglades region of south Florida. Freshwater inflows drive salinity conditions, and salinity is the primary stressor on their ecology. Comprehensive Everglades Restoration Plan (CERP) projects aim to improve the quantity, quality, and timing of freshwater inflows for the benefit of the ecosystem.

The Restoration, Coordination, Verification (RECOVER) Northern Estuaries program monitors long-term trends of several ecological indicator species ("indicator species") and will assess CERP impacts as projects come online. These species include the Eastern oyster (*Crassostrea virginica*), and the freshwater/oligohaline submerged aquatic vegetation (SAV) species tape grass (*Vallisneria americana*) and the marine SAV species shoal grass (*Halodule wrightii*). Data from experimental and field-based studies on organism responses to changes in salinity, information from peer-reviewed and gray literature, and long-term monitoring data were used to set salinity ranges around conditions of optimum, stressful, and damaging effects for each indicator species. The CH3D hydrodynamic model used the daily historical flow data from a 50-year period of record (1965–2015) to drive a simulation of salinity, from which 14-day average salinity outputs were derived and formed the basis of the relationship between flow and salinity for the CRE and SLE. A conceptual habitat area approach was used to query the established salinity-flow database to parse flow envelopes that would produce maximum potential habitat area that fall into the Optimum Salinity ranges for each indicator species. Salinity maps were used to select Optimum Flow Envelopes, and for establishing Stress and Damaging Flow regimes, based on resulting salinities throughout each estuary, and their potential physiological or ecological impacts to indicator species.

	Flow Envelopes in cubic feet per second (cfs)			
Estuary	**2007 PM Target**	**2020 Optimum**	**2020 Stress**	**2020 Damaging**
St. Lucie	350–2000	150–1400	1400–1700	>1700
Caloosahatchee	450–2800	750–2100	2100–2600	>2600

For the purposes of CERP project alternative evaluation, the distribution of 14-day moving average flows over the 50-year modeling period of record (POR) in each Flow Envelope will be generated from the Regional Simulation Model (-Basins [RSM-BN]). Ideally, project alternative simulations over the POR would yield no more than two (2) consecutive 14-day moving average flow periods in the Stress Flow Envelope, and no more than one (1) consecutive 14-day moving average flow periods in the Damaging Flow Envelope, in either the SLE or CRE. More Optimum

DRAFT

Flows and fewer repeated Stress or Damaging Flows are better. Additional RSM-BN outputs described in the Evaluation Application (Section 3) will be generated to inform project alternative performance relating to magnitude, duration, and return frequency of flows, and relative contributions from Lake Okeechobee Regulatory Releases and basin runoff, for which specific targets need to be developed for future Salinity Envelope PM updates. Updates will continue as new science, modeling tools, and further insight through long-term Northern Estuaries monitoring and other studies becomes available.

1 PURPOSE, BACKGROUND, AND JUSTIFICATION

1.1 Introduction

The Restoration, Coordination, Verification (RECOVER) Program is the scientific arm of the Comprehensive Everglades Restoration Plan (CERP) and aims to support restoration using the best available and current science for project planning ("evaluation"), project implementation success ("assessment"), and adaptive management.

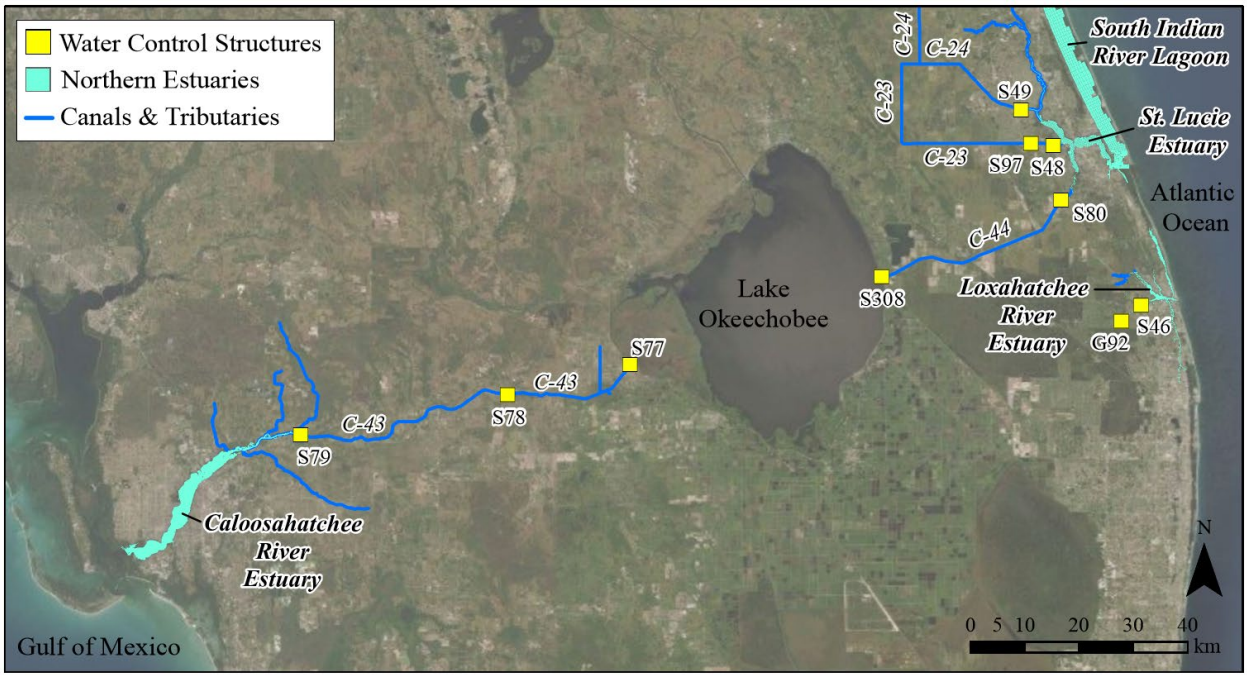

***Figure 1**. The Caloosahatchee, St. Lucie, and Loxahatchee Estuaries relative to Lake Okeechobee and the greater Everglades ecosystem*

The purpose of the Northern Estuaries Salinity Envelope Performance Measure (PM) is to provide biologically and ecologically driven guidance for establishing and maintaining salinity regimes that sustain healthy estuarine ecosystems in the St. Lucie Estuary (SLE), Southern Indian River Lagoon (S-IRL), Loxahatchee River Estuary (LRE), and the Caloosahatchee River Estuary (CRE) in the northern Everglades region of south Florida (Figure 1). The previous version of this PM was written in 2007 (RECOVER 2007a). This update incorporates older and new studies and monitoring data since 2007 (Section 2.2), and advanced watershed and hydrodynamic modeling tools to simulate freshwater inflow scenarios impacting salinity. The

Northern Estuaries have faced major physical, biological, and hydrologic alterations from their historical state due to construction and operation of the Central and Southern Flood Control District (C&SF) canals, and resultant urban and agricultural development afforded by enhanced drainage and flood protection. Each estuary faces unique challenges, but the primary stressor among them is an altered salinity regime due to changes to the quantity, quality, and timing of freshwater flows from the pre-drainage condition.

1.2 St. Lucie Estuary

The St. Lucie Estuary (SLE) straddles south St. Lucie County and north Martin County and is one of the largest brackish water bodies along the Atlantic coast of Florida (**Figure 2**). The drainage area of the SLE is a comparatively large area with an approximate watershed-to-estuary ratio of 100:1 (South Florida Environmental Report; SFWMD 2020a). It intersects the southern Indian River Lagoon (S-IRL) and intracoastal waterway, with several sources of freshwater inflow, including the C-24, C-23, and St. Lucie River/C-44 canals, with tidal flushing provided through the adjacent St. Lucie Inlet (**Figure 2**).

Historically, the SLE was a freshwater system only occasionally exposed to the ocean through ephemeral passes in the barrier islands (SFWMD 2020a). The St. Lucie Inlet was permanently opened in 1892 (SFWMD 2020a). The SLE receives water from Lake Okeechobee, which is conveyed through the S-308 water control structure at the lake, through the C-44 canal, and out of the S-80 structure into the South Fork (**Figure 1**). Sources of inflow into the North Fork occur through the C-23 canal and S-48 structure, through the C-24 canal and S-49 structure, and additional small tidal creeks (**Figure 1**). The upstream boundary of the middle and lower estuary is at the US1 Roosevelt Bridge and A1A Bridge, respectively. The long-term (WY1997–WY2019) annual average inflow and percent contribution of inflow from Lake Okeechobee are 0.31 million acre-feet (ac-ft) and 27%, respectively; and long-term annual average inflows and contributions from basin runoff are 0.7 million ac-ft and 73%, respectively (SFWMD 2020a). The SLE has a total surface of 29 km^2, with an average depth of 2.4 m, and a flushing time of approximately 2–20 days (average 7 days; Ji et al. 2007; Buzzelli et al. 2013b).

Significant effects to changes in salinity in the SLE are caused by high volumes of inflow from the watershed and Lake Okeechobee Regulatory Releases during periods of high precipitation in the wet season (generally May–October), major tropical storms, hurricanes, and climatic events associated with El Niño. For example, following Hurricane Irma in September 2017, large volumes of inflow to the estuary caused the entire system to become fresh (salinity <5) for 37 consecutive days, of which 22 days salinities were <1 (M. Parker, pers. Comm; see Fish & Wildlife Research Institute report [FWRI 2018] for more info on impacts from Hurricane Irma on SLE oysters). Salinity at the US1 US1 Roosevelt Bridge was <10 for three months (SFWMD 2020a). These episodic, often extended periods of low salinity have major impacts on the ecosystem, and in 2017 led to a die-off of oysters at all the RECOVER monitoring stations.

Other impacts to the SLE include harmful algal blooms (HABs), exacerbated by nutrient-laden inflows or by transport of phytoplankton from upstream sources; but the Salinity Envelope PM is not designed to address water quality or HABs, and any future evaluation and assessment water quality PMs would require predictive modeling tools not available at this time.

DRAFT

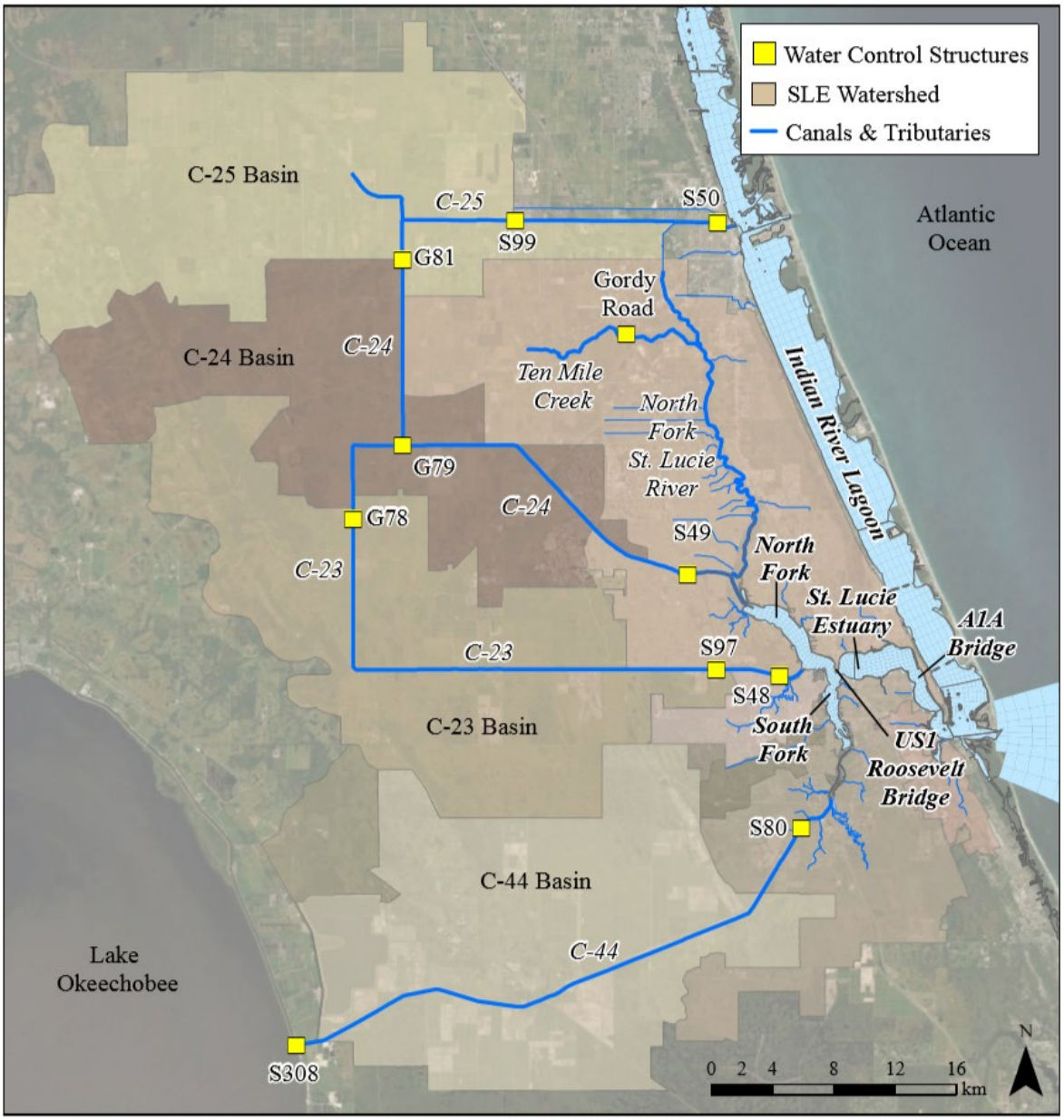

***Figure 2**. The St. Lucie Estuary relative to proximity to major waterbodies and sources of inflow*

The 2007 Salinity Envelope PM established flow envelopes of 350–2000 cubic feet per second (cfs) from all sources of inflow, including groundwater, surface water, and Lake Okeechobee water as suitable to maintain salinities conducive to shoal grass and oysters (salinity 12–20) at the US1 Roosevelt Bridge (RECOVER 2007a). Full restoration targets based on simulations of historic flow and rainfall over a 36-year period of record (POR 1965–2000) included:

- 31 months (out of 432 months in the POR) where mean monthly flow was <350 cfs;
- Zero (0) Lake Okeechobee Regulatory Discharge events >2000 cfs over 14-day moving average; and
- 28 local basin flow events >2000 cfs over 14-day moving average.

1.3 Loxahatchee River Estuary

The Loxahatchee River Estuary (LRE) is in north Palm Beach County, Florida (Figure 3). Its watershed is expansive, at around 435 km^2 and a 175:1 watershed-to-estuary ratio; but historically, the watershed drained more than 565 km^2 of sloughs and wetlands, including pine flatwoods, hardwood swamps, marshes, and wet prairies (VanArman et al. 2005). The LRE is connected to the Atlantic Ocean through the Jupiter Inlet, and connects to the southern terminus of the IRL. The Intracoastal Waterway continues south and eventually meets with the northern Lake Worth Lagoon in North Palm Beach. The existing watershed still includes major freshwater systems including the Loxahatchee Slough, Grassy Waters Preserve, J.W. Corbett Wildlife Management Area, and Jonathan Dickinson State Park (VanArman et al. 2005).

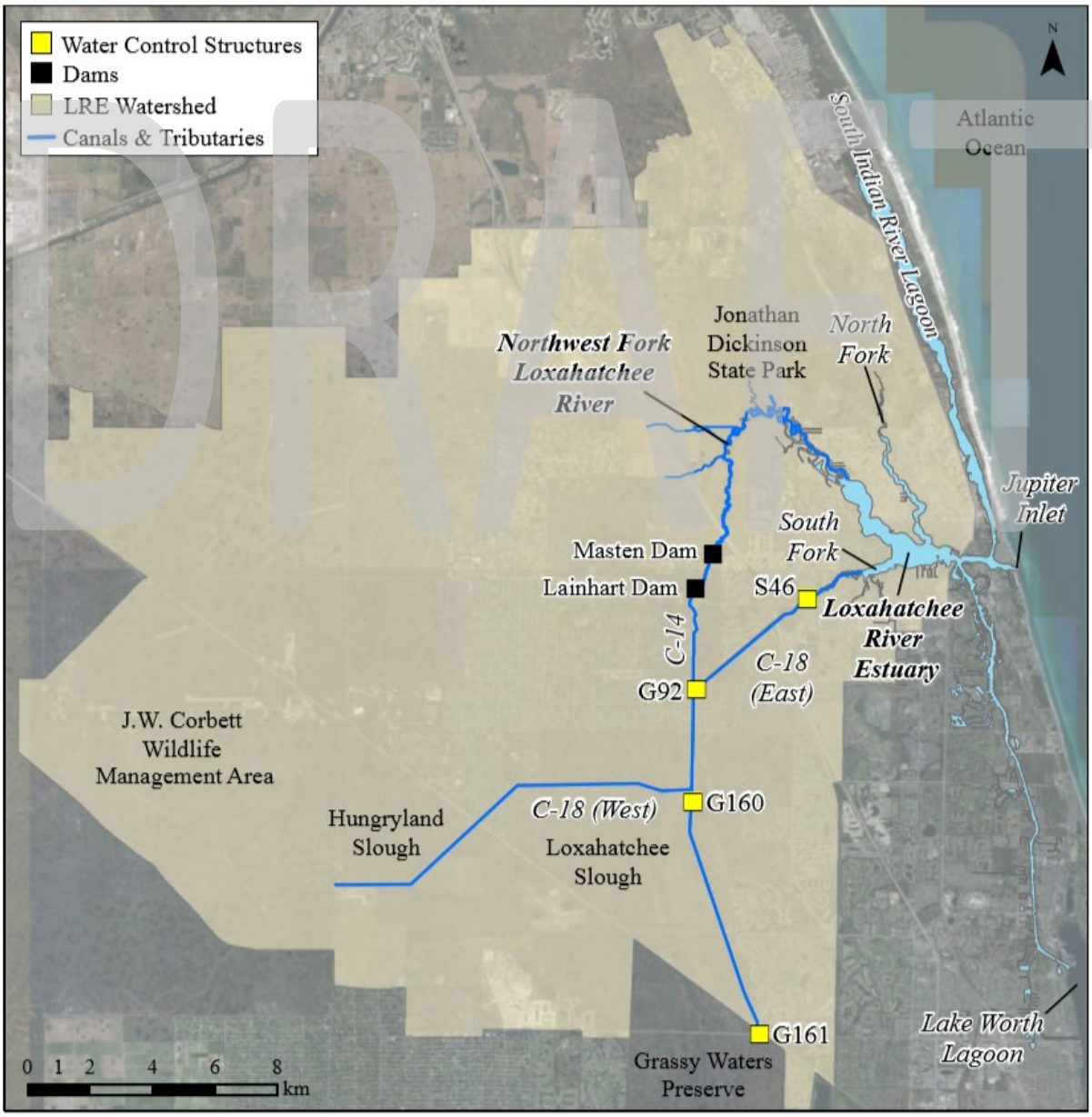

***Figure 3**. The LRE and major tributaries including the Northwest Fork*

The Northwest Fork of the Loxahatchee River is a major tributary of the LRE and was impacted both by the construction of the Lainhart and Masten Dams in the 1930s and the C-18 Canal in the 1950s, which was built to divert water to the Southwest Fork of the LRE. To mitigate the reduced freshwater flows, the C-14 was improved and G92 water control structure constructed in the 1970s to redirect water into the Northwest Fork (**Figure 3**). The dams were re-constructed in the 1980s (Restoration Plan for the Northwest Fork of the Loxahatchee River [Restoration Plan] 2006) and refurbished in 2017.

The historic, once ephemeral Jupiter Inlet was made permanent in 1947, and coastal development altered the estuary's hydrology. The reduction of freshwater flows to the Northwest Fork combined with the permanent connection to the Atlantic Ocean led to shifts in floodplain vegetation as saltwater moved upstream where mangrove species have displaced cypress and wetland plant communities (VanArman et al. 2005).

In 2006, the Restoration Plan for the Northwest Fork of the Loxahatchee River found that the preferred restoration flow scenario is a variable dry season flow of 50–110 cfs, with mean monthly flow of 69 cfs over the Lainhart Dam, and another 30 cfs from downstream tributaries (Restoration Plan 2006). Flow-salinity relationships were re-evaluated in 2011 and found to be consistent with the targets as outlined in the Restoration Plan (2006) (Addendum to the Restoration Plan 2012). As such, this document will not contain additional updates on the LRE PM flows.

1.4 Caloosahatchee River Estuary

The Caloosahatchee River Estuary (CRE) is located on the lower west coast of Florida, in Lee County (**Figure 4**). Historically, the river extended upstream to Lake Flirt approximately 3.2 km east of La Belle, and in the 1880s was straightened, deepened, and extended to connect to Lake Okeechobee (SFWMD 2020a). The river, now the C-43 canal, extends from Lake Okeechobee to the S-79 structure. The S-79 water control structure (also called the Franklin Lock and Dam) located 70 km downstream of the S-77 structure at Lake Okeechobee is where tidal waters are prevented from moving upstream into the C-43 and is considered the upstream boundary of the estuary (**Figure 1**; SFWMD 2020a).

The current watershed for the Caloosahatchee River Minimum Flow and Level (MFL) includes the S-4 basin adjacent to Lake Okeechobee, East and West Caloosahatchee Basins, the Tidal Basin located downstream of S-79 (SFWMD 2020a). The long-term (WY1997–WY2018) annual average inflow and percent contribution of Lake Okeechobee are 0.62 million ac-ft and 33%, respectively (SFWMD 2019). The surface area of the CRE is 55.9 km^2, with an average depth of 2.7 m, and a flushing time of approximately 2–30 days (average 18.4 days; Buzzelli et al. 2013b). In addition to high flows and reductions in salinity downstream in the CRE, base flows during the dry season are required to prevent saltwater intrusion affecting oligohaline/mesohaline-adapted SAV upstream of the Highway 41 Bridge (Figure 4).

DRAFT

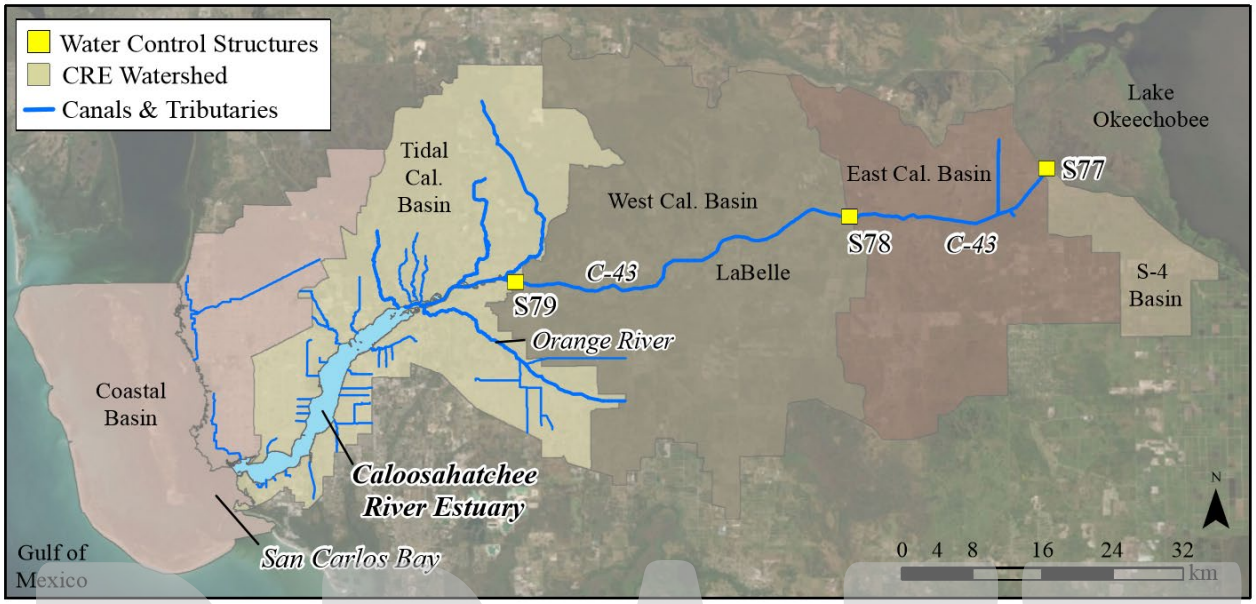

***Figure 4**. The CRE relative to its proximity to major waterbodies and sources of inflow*

The 2007 Salinity Envelope PM established flow envelopes of 450–2800 cfs as measured at S-79 to reduce minimum discharge and high flow events (RECOVER 2007a). The low flows within this bracket was based on a flow volume slightly above the Minimum Flow and Level (MFL) for the CRE at the time, while the high flow bound was based on flows required to prevent low salinity in the lower CRE near Shell Point and into San Carlos Bay (salinity value not specified; RECOVER 2007a). Full restoration targets based on simulations of historic flow and rainfall over a 36-year period of record (POR 1965–2000) included:

- Zero (0) events (out of 432 months in the POR) mean monthly flow <450 cfs;
- Zero (0) events mean monthly flow >2800 cfs;
- 75% of flows through S-79 within range of 450–800 cfs; and
- Fewer Lake Okeechobee Regulatory Discharges, exempting for pulse releases deemed beneficial to the estuary.

The MFL for the Caloosahatchee River was re-evaluated and updated from 300 cfs to 457 cfs at the S-79 structure (SFWMD 2020b). The revised rule for the MFL of 457 cfs at S-79 became effective in December 2019 (40E-8.221[2], Florida Administrative Code).

2 DESIRED RESTORATION CONDITION

2.1 CERP Implementation and Expectations for Restoration

The Northern Estuaries are highly altered systems situated in a water management infrastructure dependent on operations driven by natural stochasticity of weather and multiple human demands including flood protection, health and safety, and water supply. A restoration goal consistent with a pre-drainage condition is not tenable in the Northern Estuaries (e.g., the St. Lucie was a freshwater body whose modern connection to the Atlantic Ocean through the St. Lucie Inlet is, pragmatically if not literally, irreversible). The RECOVER PM for salinity in Florida Bay

DRAFT

includes setting targets based on paleosalinity data and the South Florida Water Management District's (SFWMD) Natural Systems Model (NSM) within its sub-basins (RECOVER 2012). Not only would a comparable target for the Northern Estuaries be impractical, but there is no paleo/historical dataset commensurate with that in Florida Bay.

Therefore, in the context of "Restoration," what CERP aims and has the capacity to do in the Northern Estuaries is restore critical hydrologic characteristics with the reduction in incidences of flows that would result in salinity conditions not conducive to supporting the health and diversity of the existing estuarine ecosystems. Total CERP Implementation Goals include a reduction in 80% volume of flows and undesirable high discharge events to the Northern Estuaries. Additional RECOVER PMs for oyster habitat and SAV based on acreages were developed in 2007 (RECOVER 2007b; 2007c, respectively), but these require future updates as evaluation tools are not currently available.

There are many ways to define critical hydrologic characteristics, including monthly flow distributions, flow patterns, runoff volume, and others (IRL-South Project Implementation Report and Environmental Impact Statement [IRL-S PIR/EIS] 2004). The previous Northern Estuaries Salinity Envelope PM (RECOVER 2007a) and Restoration Plan for the Northwest Fork of the Loxahatchee River (Restoration Plan 2006; Restoration Plan Addendum 2012) provide flow envelopes with a lower and upper boundary, outside of which the salinities in the estuary could negatively impact certain species of interest. For the SLE and CRE, these envelopes were based on flows which result in salinities at a single location within either estuary (e.g., salinities of 12–20 at the US1 US1 Roosevelt Bridge for the SLE). Described later in this PM Documentation Sheet, the updated Salinity Envelope PM aims to add a spatially-explicit component by setting salinity envelopes relevant to the whole system along the gradient of the estuary, rather than at a single location; and to the extent possible consider other factors such as duration and return frequency of flows outside the chosen envelope for each estuary. The previous version of the Salinity Envelope PM (RECOVER 2007a) includes limited information or evaluation or assessment criteria regarding duration of violations outside of the desired flow envelopes.

The species monitored in the Northern Estuaries were chosen based on the U.S. Environmental Protection Agency valued ecosystem component (VEC) approach (USEPA 1987, as cited in IRL-S PIR/EIS 2004). VECs, or ecological indicator species, referred to henceforth as "indicator species," perform a key function in an ecosystem including the provision of habitat as living spaces, refugia, and foraging ground for other desirable species (IRL-S PIR/EIS 2004). The indicator species for the Northern Estuaries include the Eastern oyster (*C. virginica*) and species of SAV adapted to varying salinity regimes (e.g. tape grass [*V. americana*]; shoal grass [*H. wrightii*]). Key hypotheses supporting the selection of these species as ecological indicators are outlined in the RECOVER 2009 Monitoring and Assessment Plan (MAP) (RECOVER 2009).

2.2 Northern Estuaries Ecological Indicators in Relation to Target Salinity Envelopes

The indicator species for the Northern Estuaries include the Eastern oyster (*C. virginica*), a bivalve common along the Atlantic coast of the United States and the Gulf of Mexico that tolerates a range of salinities from the mesohaline to marine (Galtstoff 1964; Cake 1983;

Mackenzie 2007; Lu et al. 2008; Lowe et al. 2017); and the following species of submerged aquatic vegetation (SAV): tape grass (*V. americana*) which prefers freshwater to oligohaline conditions (Twilley and Barko 1990; Doering et al. 2002; Lauer et al. 2011); and shoal grass (*H. wrightii*), a mesohaline-adapted marine SAV (Zieman and Zieman 1989; Doering et al. 2002; Buzzelli et al. 2014; Rivera-Guzmán et al. 2014).

There are a total of seven mesohaline/marine SAV known in Florida estuaries. In addition to shoal grass, these include turtle grass (*Thalassia testudinum*), manatee grass (*Syringodium filiforme*), widgeon grass (*Ruppia maritima*), paddle grass (*Halophila decipiens*), star grass (*Halophila engelmannii*), and the only federally-listed endangered SAV species, Johnson's grass (*Halophila johnsonii*). Tape grass and shoal grass are the two species of focus in this PM due to their salinity tolerances which are representative of the conditions observed at either end of the salinity gradient and desired for hydrological restoration in the Northern Estuaries.

An examination of peer-reviewed and gray literature pertaining to the physiological responses and ecological tolerances of these indicator species to salinity (Section 2.2) was conducted prior to model development of flow targets (Section 3). The 2007 Salinity Envelope PM flow targets were predicated on target salinities as well, but were not separated by individual species: the SLE 350-2000 cfs flow envelope was based on establishing salinities 12–20 at the US1 US1 Roosevelt Bridge (middle estuary) for both shoal grass and oysters (Section 1.2); and the CRE flow envelope was informed by the previous CRE MFL for the low flow bound, and at the high flow end by flows required to prevent low salinities in the lower estuary near Shell Point and San Carlos Bay (salinity value not specified; Section 1.4).

For this PM update, in addition to the Optimum Salinity Envelope for each species, the salinity ranges that are sub-optimum and deleterious to critical organismal or ecological function were identified and defined henceforth as "Stress" and "Damaging" Salinity Envelopes, respectively. The reviewed literature included a diverse set of response variables, varying durations of exposure to salinity conditions, within which were field and laboratory experimental studies, and observations or trend analysis from monitoring data. All salinities reported throughout this document are unitless (Unesco 1981).

Study results, monitoring data, and other information from the literature (Sections 2.3–2.5) were compared to establish Optimum, Stress, and Damaging Salinity Envelopes for each indicator and are generally defined per the following (**Table 1**):

- **Optimum Salinity Envelopes** – salinities yielding the greatest performance of measured response variables (e.g., good measures of growth, density, recruitment, photosynthetic capacity, osmoregulation, respiration; low disease prevalence and intensity, oxidative stress, predation) indicative of healthy organisms or wild populations/habitats.
- **Stress Salinity Envelopes** – salinities yielding a decline in performance of one or more response variables, but tolerable for short-term exposures. Prolonged durations of exposure to stressful salinities may result in loss of the indicator.
- **Damaging Salinity Envelopes** – salinities yielding significant declines in performance of one or more response variables even with short-term exposure and can result in loss of the indicator with prolonged or repeated exposure.

DRAFT

Sections 2.3–2.5 provide the supporting evidence used to develop the Optimum, Stress, and Damaging Salinity Envelope ranges (**Table 1**), which were used to aid the statistical modeling of flow envelope categories using the same criteria, in which the range of flows (i.e. Optimum Flows, Stress Flows, and Damaging Flows) produce salinities of the corresponding category. The flow-salinity relationship in each estuary was modeled using the CH3D hydrodynamic salinity model, using approximately 50 years of observed and modeled data (Appendix A).

***Table 1**. Optimum, Stress, and Damaging Salinity Envelopes for Northern Estuaries indicator species, which aided the modeling of flow envelopes. The 2007 Salinity Envelope PM targets in the SLE were based on salinities 12–20 at the US1 Roosevelt Bridge for both shoal grass and oysters; and the targets in the CRE based on the previous CRE MFL and preventing low salinities in the lower estuary near Shell Point and San Carlos Bay (salinity value not specified; RECOVER 2007a).*

	2007 PM	2020 PM		
Species	**Targets**	**Optimum**	**Stress**	**Damaging**
Eastern oyster (adult)	12–20 (SLE)	10–25	5–9; >25	<5
Tape Grass	<10 (CRE MFL)	<10	10–15	>15
Shoal Grass	12–20 (SLE)	15–45	5–14; >45	<5

2.3 Eastern Oyster

An Optimum Salinity Envelope of 10–25 for the Eastern oyster (*Crassostrea virginica*) was selected and predicated upon balancing conditions most likely to benefit performance of the greatest number of physiological and ecological responses as summarized below.

Generally, adult oysters are tolerant of a wide range of salinity from 5–40, although within either ends of this range, negative impacts are observed (Galtstoff 1964; Cake 1983; Volety et al. 2009). Maximum oyster growth generally occurs toward the higher end of this optimum salinity range (Volety et al. 2003; Shumway 2006). However, at higher salinities, Dermo infection and predation can affect oyster survival and recruitment (Gunter 1955; Wilson et al. 2005; La Peyre et al. 2009; Barnes et al. 2010; Carroll et al. 2015; Kimbro et al. 2017). Higher salinity can increase the prevalence of parasitic infection from *Perkinsus marinus* (Dermo); Dermo prevalence and intensity tends to be higher in the CRE at the two downstream sites (Bird Island and Kitchel Key) than the upstream sites (Iona Cove and Peppertree Point) of lower salinity (RECOVER 2019), and a decline of infection intensity has been observed in the SLE and CRE following salinity reductions (La Peyre et al 2003; Wilson et al 2005). La Peyre et al. (2003) recommended controlled freshwater releases as an adaptive management strategy to combat disease. However, the influence of Dermo may be limited in the CRE due to the subtropical climate and seasonality, where temperature is low when salinity is high in the dry season, and temperature is high when salinity is low in the wet season (SFWMD 2020b).

At salinities >20, marine predators and pests (e.g., oyster drills, boring sponges, crabs, and fish such as black drum) can infiltrate oyster reefs (Gunter 1955; Brown 2008; Barnes 2010; Carroll 2015; Kimbro 2017). A field study comparing oyster populations in Ochlockonee and Apalachicola Bays in north Florida, two estuarine systems that exhibit similar rainfall but

DRAFT

differing levels of freshwater inflow, observed that Apalachicola Bay had an outbreak of predators; while the other population of oysters in Ochlockonee Bay was protected from the predators near the river mouth due to higher river inputs and resultant lower salinity relative to Apalachicola Bay (Kimbro et al. 2017). Carroll et al. (2015) found that sponge-colonized oysters had lower growth rates and condition index (CI) than uncolonized oysters. The boring sponge (*Cliona* sp.) also decreased oyster larval settlement and increased mortality in a microcosm study of oyster reef community interactions (Barnes et al. 2010). While more studies are needed to inform the interactions of boring sponges with oysters in the Northern Estuaries, the sponge has been observed in San Carlos Bay.

Volety et al. (2003) found that oysters in the CRE grew best at salinities 14–28, with highest spat recruitment and low disease prevalence at intermediate salinities of 10–20. They observed >95% mortality of juvenile oysters exposed to salinities <5 (Volety et al. 2003). Salinities < 5 also impair gametogenesis (Shumway 1996) and growth (Lowe et al. 2017). A study by Wilson et al. (2005) found decreased spat sets in salinity <10 in the SLE; and Salewski and Proffitt (2016) found negative impacts to oyster recruitment and survival of small oysters (<20 mm) when exposed to salinities <10 for several months. The optimum salinity envelope of 10–25 is intended to encompass beneficial salinity ranges for the multiple life stages of this indicator.

2.4 Tape Grass

An Optimum Salinity Envelope of 0–9 (<10) for tape grass (*Vallisneria americana*) was selected based on observed field data and research on adult plant, flowering, and seed germination studies available in the literature and summarized below.

Tape grass, a fresh to brackish water SAV, prefers a salinity range of zero to less than ten. A salinity exposure study on growth by Doering et al. (2002) observed no change in growth between salinity treatments of 10–15, but significant loss of shoots occurred at salinity greater than 15. Studies of flowering and seed germination observed negative effects at salinities greater than 10 (French and Moore 2003; Jarvis and Moore 2008). Some studies observed that growth may be unaffected by salinities up to 12 or 13 (Twilley and Barko 1990; Oscar et al. 2018). Others measured a physiological stress response to a salinity of 13 after a 7-day exposure, with a much more rapid response to salinity of 15 where metabolic stress responses were detected after only 24 hours (Lauer et al. 2011). At salinities higher than 15, significant shoot loss of plants was observed in a transplant study after only a few days of exposure (salinity 18; Jacoby 2012) and a 50% blade loss was observed in a mesocosm study after 38 days (salinity 18; Doering et al. 2002).

SAV physiology, growth, and reproduction responses to salinity can be confounded by other environmental parameters such as sediment, temperature, and light (Twilley and Barko 1990; Jarvis and Moore 2008; Tallerico et al. 2012; Shields and Moore 2016). When a poor light environment is concurrent with salinity stress, this can reduce the plant's overall tolerance. In the CRE, freshwater inflow (total cfs) is positively correlated to color, decreasing the light available in the water column (Doering and Chamberlain 1999). French and Moore (2003) determined that at a salinity of 5 the light requirements for tape grass may be 50% greater than that of plants at a salinity of 0, suggesting that at salinities between 10 and 5, with the addition of light stress,

DRAFT

salinity tolerance is reduced. This study determined that photosynthetic capacity of the plants was not affected by salinity stress over the period of the study and was a light-stress driven response (French and Moore 2003). In conditions of reduced light stress, a field study suggested a capacity for higher salinity tolerance, with mortality of tape grass planted at a salinity 0 site, where light was limited, and survival of tape grass planted at a salinity 20 site with higher irradiance (Kraemer et al. 1999). The possible salinity and light stress interaction effects are important to consider for tape grass in this system. Flows that produce salinities conducive to tape grass, may complicate the restoration potential of this species by reducing light availability, as light attenuation from color increases with flow, is inversely related to salinity and color (CDOM), and is a significant factor in affecting light attenuation in the upper CRE (Buzzelli et al. 2014; Chen et al. 2014; Chen and Doering 2016). Additional studies are warranted to determine which environmental conditions beyond salinity, e.g., light attenuation, drive tape grass populations in the CRE, and adaptive management strategies developed to address other stressors in the event local populations do not recover with improvements in salinity envelope alone.

2.5 Shoal Grass

An Optimum Salinity Envelope of 15–45 was selected for shoal grass (*Halodule wrightii*) based on observed monitoring data from the estuaries and field studies and research on plant responses that were available in the literature and summarized below.

Shoal grass tolerates a broad range of salinity conditions, from 10–60, with stress responses or low densities observed within the hypo- and hypersaline ends of this spectrum (Dunton 1990; McMahan 1968; Doering et. al 2002; Lirman and Cropper 2003; Koch et al. 2007; Frankovich et al. 2011; Garrote-Moreno et al. 2014; Rivera-Guzman et al. 2014). While more studies have focused on the hypersalinity tolerance and responses of this seagrass, some data are available on responses to hyposalinity stress for greater than two weeks, which is of ecological relevance for the Northern Estuaries with their relatively short flushing rates, consequently reducing the likelihood of persistent hypersaline conditions (Buzzelli et al. 2014).

A study in coastal Texas comparing shoal grass at three estuarine sites with increasing distance from freshwater inflows (resultant average salinity 17, 30, and 38) found the lowest values for total shoot and root biomass, biomass per shoot, and shoot density at the site with average salinity 17 (Dunton 1996). Field monitoring in CRE observed the highest density of blades in salinities greater than 20 and a decrease in shoot density with decreased salinity (Doering et al. 2002). A 14-day study observed highest average blade extension rates at a salinity of treatment of 35 for shoal grass collected from Biscayne Bay, with the lowest at the salinity treatments 45 and 5 (Lirman and Cropper 2003). A longer 10-week growth study of plants collected from the CRE exhibited 50% shoot loss at salinity of 3 and net zero growth at salinities 6 and 12 (Doering et al. 2002). Freshwater inflow to the CRE and SLE is high in color affecting light attenuation, with turbidity as a secondary light attenuation factor; their effects on the light environment is related to source and location in the estuary (Doering 1996; Chen et al. 2014; Buzzelli et al. 2014; Chen and Doering 2016; Stockley et al. 2018). Light availability affects shoal grass physiology, growth, survival, and depth distribution (Czerny and Dunton 1995; Kenworthy and Fonseca 1996; Burd and Dunton 2001). Due to the nature of these systems and the link between

DRAFT

color and flow, increased light attenuation conditions are likely to coincide with reduced salinity conditions, which may reduce physiological tolerance of the seagrass. Further research and modeling of these covariates' effects on this indicator is needed to better understand responses in these two systems.

3 EVALUATION APPLICATION

Performance Measures are applied during the CERP Project planning process for a RECOVER System-Wide Evaluation of project alternatives contributions toward restoration targets, the results of which are incorporated into the Project Implementation Report/Environmental Impact Statement (PIR/EIS). The following describes performance targets for the Northern Estuaries Salinity Envelope (salinity as a function of inflows in cubic feet per second [cfs]; **Table 2**), as well as hydrologic outputs to be generated from the Regional Simulation Model (-Basins [RSM-BN]) for RECOVER System-Wide Evaluation, for the SLE and CRE. Targets for the LRE are addressed in the 2011 re-evaluation of the LRE Restoration Plan and were found to be consistent with established targets as outlined in the Restoration Plan (2006) (Addendum to the Restoration Plan 2012).

As multiple indicators with different optimum salinities were used to develop targets, it was imperative to develop a single Optimum Flow Envelope for each estuary to benefit all indicator species to the greatest extent possible. Optimum Flow Envelopes for the SLE and CRE (Table 2) represent the range of flows (cfs) expected to produce optimum salinity (within the Optimum Salinity Envelope) for a given ecological indicator within their known or desired range within each estuary. Whereas, Stress Flow Envelopes and Damaging Flow Envelopes represent the range of flows (cfs) expected to produce salinities deemed stressful and damaging to *one or more* indicator species. For example, extreme high flows in the CRE could produce damaging salinities in the lower estuary for oysters, but tape grass would not be affected upstream by low salinity.

***Table 2**. Flow Envelopes determined as optimum, stressful, and damaging for the corresponding Salinity Envelopes of all indicator species in the Northern Estuaries*

Estuary	Optimum	Stress	Damaging
St. Lucie	150–1400 cfs	1400–1700 cfs	>1700 cfs
Caloosahatchee	750–2100 cfs	2100–2600 cfs	>2600 cfs

For the purpose of RECOVER System-wide Evaluation, in addition to the performance of project alternatives to improve incidence of flows in the Optimum range and decrease incidence of flows in the Stress and Damaging range, additional hydrologic data outputs from RSM-BN are described and to be included in alternative evaluation (**Table 3**). Evaluation of these hydrologic data will be based on understanding of indicator species response to salinity stress, and observations from RECOVER monitoring data in which significant damage to indicator species populations resulted from persistent or reoccurring high freshwater inflows and concomitant stressful or damaging salinities. These hydrologic data will help to address how CERP project alternatives affect the magnitude, duration, and return frequency of flows in each range defined by Table 2. Additional biological data and modeling tools are needed to establish targets based on magnitude, duration, and return frequency criteria (see Appendix C).

***Table 3**. Northern Estuaries Salinity Envelope and Hydrological Target criteria to be used in RECOVER System-Wide Evaluation of CERP Project alternatives. Outputs will be generated using the RSM-Basins.*

Hydrologic Criteria	Description of RSM-BN Outputs	Targets
Distribution of 14-day moving average Inflows to the SLE	The distribution of 14-day moving average flows (over the entire POR), including low flows (<150 cfs), flows in the Optimum Flow Envelope (150–1400 cfs), and high flows in the Stress (1400–1700 cfs) and Damaging Flow Envelope (>1700 cfs)	More periods in the Optimum Flows is better; fewer periods in the low flows, or Stress and Damaging Flows is better.
Distribution of 14-day moving average Inflows to the CRE	The distribution of 14-day moving average flows (over the entire POR), including low flows (<750 cfs), flows in the Optimum Flow Envelope (750–2100 cfs), and high flows in the Stress (2100–2600 cfs) and Damaging Flow Envelope (>2600 cfs)	More periods in the Optimum Flows is better; fewer periods in the low flows, or Stress and Damaging Flows is better. species.
SLE Flow Table	Monthly average flows to SLE at S-80 and other tributaries for each month and year over the POR.	No specific targets have been modeled at this time.
CRE (S-79) Flow Table	Monthly average flows to CRE at S-79 for each month and year over the POR	No specific targets have been modeled at this time.
High Discharge Events by Source in the SLE	High discharge 14-day ma "events" (>1400 cfs) triggered by Runoff and Lake Okeechobee Regulatory Releases	No specific targets have been modeled at this time.
High Discharge Events by Source in the CRE	High discharge 14-day moving average "events" (>2600 cfs) triggered by Runoff or Lake Okeechobee Regulatory Releases	No specific targets have been modeled at this time.

First, the distribution of 14-day moving average (ma) flows over the POR that fall within the Optimum, Stress, and Damaging Flows for each estuary will illustrate whether flows improve with new infrastructure and/or operations and represent the concomitant hydrologic changes throughout the system. These results are represented by bar graphs of the total distribution counts in below the Optimum Flow Envelope, and within each Flow Envelope as defined in Table 2, as well as counts of consecutive 14-day ma events in the low flow (below Optimum Flows) and high flow (above Optimum Flows) ranges (**Figure 5**). The scenarios which are compared include the distribution of flows assuming the following infrastructure or operations: (1) an Existing Base Condition (ECB), which includes existing infrastructure or operations during the project planning phase; (2) a Future Without Project (FWO) that includes a future scenario in which all

currently authorized projects are completed, but excludes the current project being planned; and (3) future scenarios in which all currently authorized projects are completed, and include one of several different project plans (i.e., Alternative 1, Alternative 2, Alternative 3…) representing different structures or operational plans. More periods in the Optimum Flows is better, and fewer periods in the low flows or Stress and Damaging Flows is better.

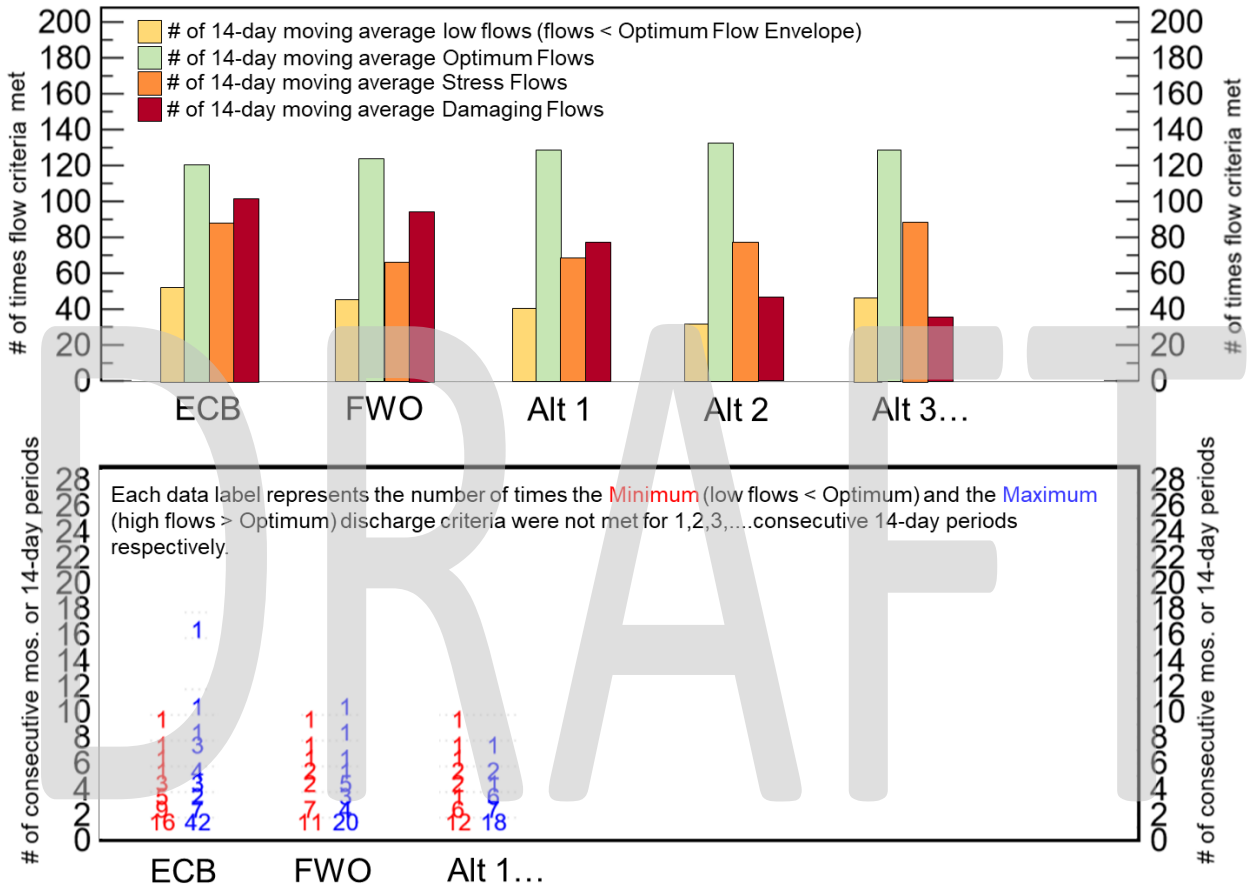

***Figure 5**. Example RSM-Basins model outputs illustrating the distribution of of 14-day moving average (ma) flows over the POR that fall below the Optimum Flow Envelopes, and fall within the Optimum, Stress, and Damaging Flow Envelopes for either estuary (top) and counts of consecutive 14-day ma events in the low flow (below Optimum Flows) and high flow (above Optimum Flows) range (bottom). Outputs compare the distribution of flows assuming Existing Base Condition, Future Without Project, and several project alternatives.*

Second, flow tables which show the monthly average flows to the SLE at S-80 and other tributaries, and to the CRE at S-79 for each month and year over the entire POR modeled for project planning, will address performance of project alternatives based on resulting magnitude and timing of flows, including duration and return frequency of Stress and Damaging Flows. These results are represented by a table in which each cell represents a monthly average flow (Month & Year, totaling 600 months), and color-coded as either low flow (below the Optimum Flow Envelope), Optimum Flows, and high flows in the Stress Flow and Damaging Flow range. Additional salinity and ecological modeling tools are needed to set targets based on duration and return frequency of flows, which are needed to address resiliency of the estuaries to long or

repeated deleterious conditions (Appendix C). These flow tables will allow members of a RECOVER System-wide Evaluation team to determine potential reduction of these Stress and Damaging conditions between project alternatives, including but not limited to comparing the timing of these conditions with oyster spawning or the SAV growing season.

Finally, results that indicate whether the number of "high flow events" (greater than the Optimum Flow Envelope) was triggered by flows from Lake Okeechobee Regulatory Releases, or from basin runoff throughout the POR, will address project-specific benefits. For example, if a project plan includes infrastructure or operation changes that are meant to direct flows away from the estuary (e.g., via storage or conveying "flows south"), it could be expected that high flow events triggered by Lake Okeechobee Regulatory Releases would decline.

Salinity Envelope PM updates will continue as new science, modeling tools, and further insight through long-term Northern Estuaries monitoring becomes available.

4 REVISED FLOW ENVELOPES AND BENEFITS COMPARED TO 2007 PM

The following sections provide a summary discussion of the processes from which Flow Envelopes (Table 2) were derived, with detailed methodological descriptions in Appendix A and B.

4.1 Selecting Optimum Flow Envelopes

To narrow the scope of possible Optimum Flow Envelopes evaluated, a habitat area-based approach was applied, by which flow ranges that can maximize the potential habitat area (PHA) – the area where salinities meet the Optimum Salinity Envelope in the estuary for a given organism – was identified. For this purpose, a hydrodynamic CH3D model (Appendix A) was used for a long-term simulation (1965–2015) of the salinity-flow relationship in each estuary. The resulting output salinities (14-day average) together with 14-day moving average freshwater inflow formed a database which was queried for different flow ranges that produce optimum average PHA over the period of record. Background and calibration of the CH3D model for the SLE and CRE is described in Appendix A.

This process produced a limited number of alternative Flow Envelopes for each estuary whose PHA performance was indicative of improvement compared to 2007 PM flow envelope PHA performance. Detailed methods and results is described in Appendix B.

Of these narrowed down, alternative Flow Envelopes, salinity maps which represent the average salinity for a given alternative (the flow between the low flow bound and high flow bound) were produced using modeled salinities from the CH3D model. Additionally, maps of percentage of time when salinity meets the Optimum Salinity Envelope for each alternative Flow Envelope and for each indicator were generated. These maps combined were used to facilitate the selection and evaluation of these alternatives for the development of this Salinity PM update. The final recommended Flow Envelopes are described below.

DRAFT

4.1.1 Results: Selected Optimum Flow Envelopes

4.1.1.1 Improvement to Salinity with Optimum Flow Envelope for the SLE 150–1400 cfs

The revised Optimum Flow Envelope target of 150–1400 cfs for the SLE provides the greatest benefit around US1 Roosevelt Bridge and into the North and South Forks.

With this revised flow range, salinity conditions of 25–35 for shoal grass improves downstream of A1A in the lower estuary, and salinity 15–24 in the Forks and upstream of the US1 Roosevelt Bridge at the juncture where the Forks split (Figure 6; left maps). Note that modeled salinities in the optimum range never reached the maximum of 45, and rather are symbolized in salinity bins of 15–24 and 25–35. Percent time of 80–100% in the optimum salinity envelope for shoal grass is further upstream in the updated PM, and 60–100% through the middle estuary (Figure 6; right maps).

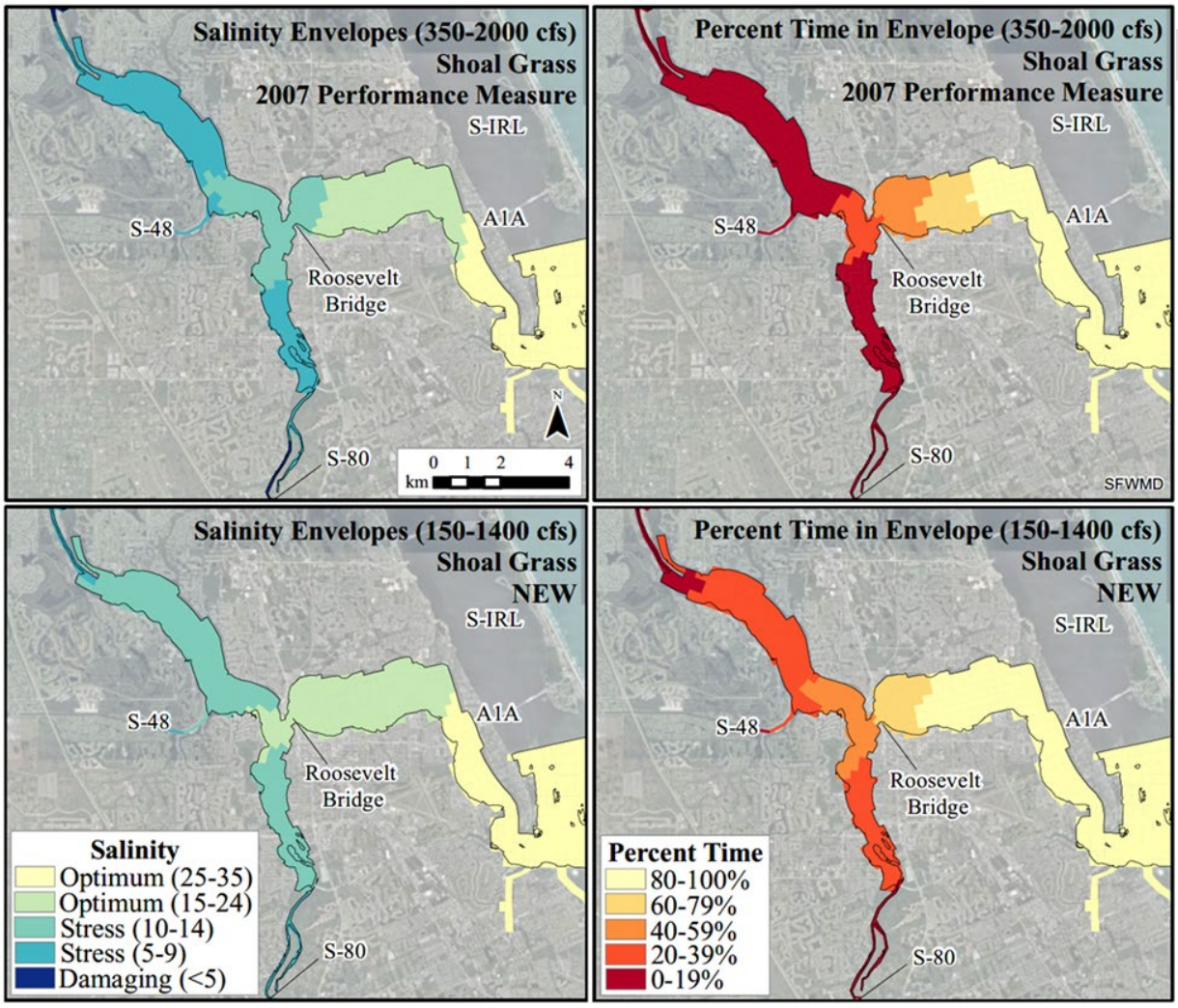

***Figure 6**. Mean salinity and percent time within Optimum Salinity Envelope for shoal grass (salinities 15–45) in the SLE modeled on target flows from the 2007 PM (350–2000 cfs) and the new, revised PM (150–1400 cfs). With the new, revised flow target, salinity conditions improve to optimum throughout the middle estuary.*

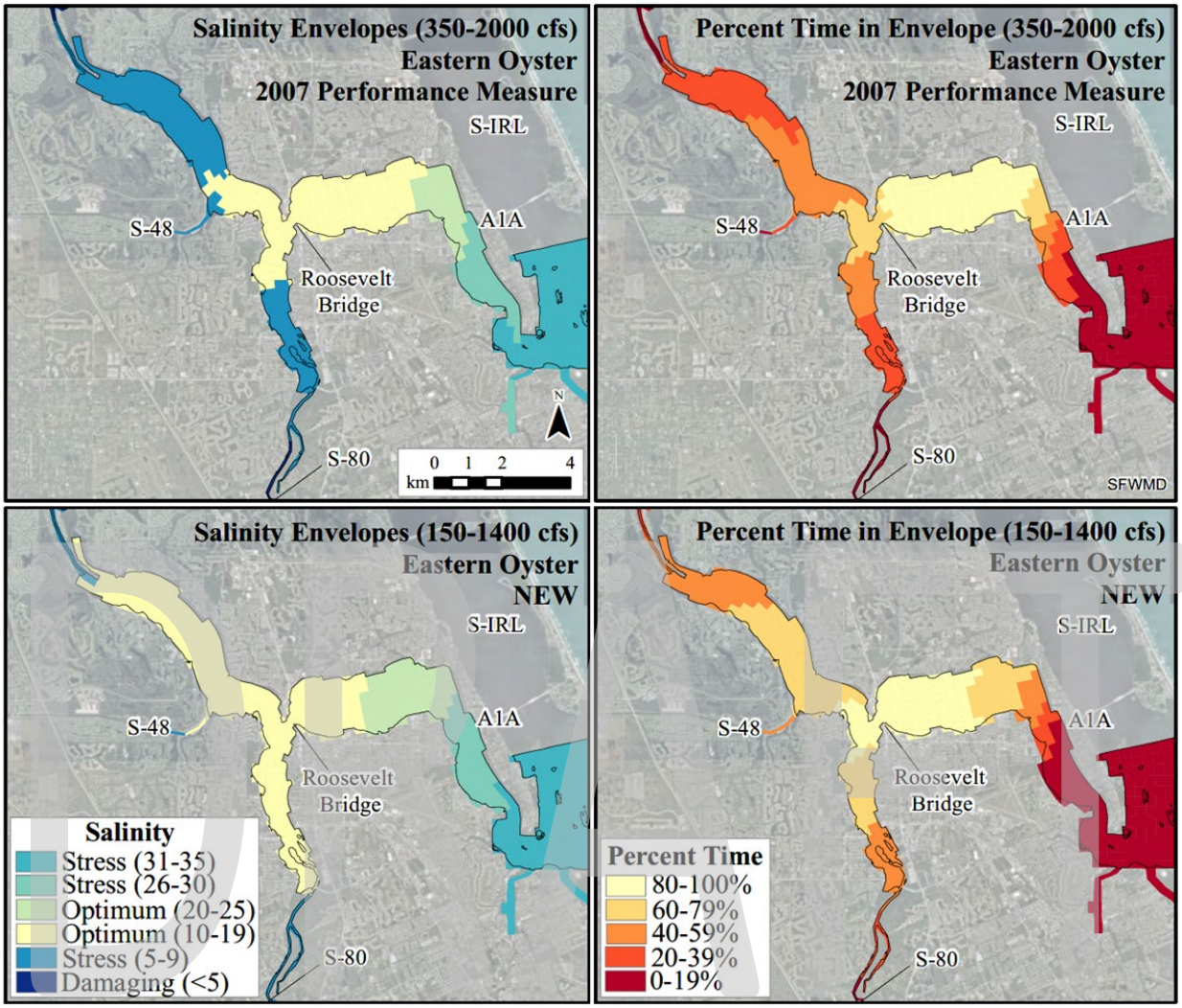

***Figure** 7. Mean salinity and percent time within Optimum Salinity Envelope for Eastern oyster (salinities 10–25) in the SLE modeled on target flows from the 2007 PM (350–2000 cfs) and the new, revised PM (150–1400 cfs). With the revised flow target, salinity conditions improve to optimum throughout most of the estuary from near A1A through the forks; and percent time in the salinity envelope is >60% of time throughout both the North and South Fork, and >80% at the juncture of the Forks beyond the US1 Roosevelt Bridge and most of the middle estuary.*

For oysters with the revised flow target, salinity conditions improve to Optimum range throughout most of the estuary near A1A and upstream through the forks, increasing the salinity envelope area relative to 2007 (**Figure 7**; left maps). Salinities 15–24 are through most of the middle estuary and past the US1 Roosevelt Bridge at the juncture of the forks. Salinities 10–14 are throughout the remainder of the Forks, which is a significant improvement for known oyster populations upstream relative to the 2007 PM targets. Oysters have been found throughout the Forks; however, the RECOVER monitoring data demonstrate that oysters at these monitoring sites have densities that rarely exceed 100 oysters m^2 (RECOVER 2019). Population densities of oysters in the middle estuary are generally an order of magnitude greater at 500–1000 oysters m^2 (RECOVER 2019) where the salinity has been more beneficial for this organism. The revised flow envelope also improves the percent time in the Optimum Salinity Envelope for oysters

(salinities 10–25). Immediately upstream of A1A, the percent time within envelope does not fall below 40%; it is >80% throughout most of the middle estuary and upstream of the US1 Roosevelt Bridge, and 60–79% throughout most of the North and South Forks (**Figure 7**; right maps).

While the revised flow targets improve the percent time in the Optimum Salinity Envelope for shoal grass, additional factors such as substrate suitability and light availability for SAV in the SLE are continuing problematic factors driving its distribution beyond A1A. Whereas, if the Optimum Flow Envelope of 150–1400 cfs is met, there is potential for major improvement to the density and health of oysters and their ecosystem services such as habitat structure and water filtration throughout most of the SLE. While the simulations are based on long-term means, extreme weather events can still result in high inflows and low salinities throughout the entire SLE to the detriment of these species. However, the number of excursions outside the Optimum Salinity and Flow Envelopes are expected to decrease with CERP project implementation.

4.1.1.2 Improvement to Salinity with Optimum Flow Envelope for the CRE 750–2100 cfs

The revised Optimum Flow Envelope target of 750–2100 cfs for the CRE provides the greatest benefit in mean salinity and percent time in its Optimum Salinity Envelope for tape grass in the area upstream of Ft. Myers. Some improvements for shoal grass and oysters are evident mainly with percent time in their respective Optimum Salinity Envelopes rather than mean salinity.

The ranges of salinities 0–5 and 5–9, Optimum for tape grass, extend further downstream with the revised flow target relative to the 2007 Salinity Envelope PM (**Figure 8**; left maps). Percent time in the Optimum Salinity Envelope for tape grass (salinity <10) improves to 80–100% near Ft. Myers, and 60–80% further downstream (**Figure 8**; right maps). Restoration of tape grass to Ft. Myers has been a goal of CRE stakeholders and includes activities such as transplants of both tape grass and widgeon grass (*R. maritima*) in the upper estuary. Improving the time in which salinity in the upstream CRE is suitable for tape grass is a significant improvement, but other factors including water color (Doering and Chamberlain 1999; Kraemer et al. 1999; French and Moore 2003) and grazing by estuarine organisms affect transplant success and overall distribution (D. Ceilley, pers. comm).

Slight improvement in percent time in the shoal grass Optimum Salinity Envelope (salinity >15) in the range of 80–100% is evident approximately 1–2 km upstream from the previous extent (**Figure 9**; right maps). Percent time in the shoal grass Optimum Salinity Envelope decreases to <20% for most of the area upstream of Cape Coral, which is expected considering the increase in low bound target flows for the benefit of tape grass. Salinity remains >25 in the lower estuary near Shell Point and into San Carlos Bay, which is within the Optimum range for shoal grass, but is also beneficial to other marine species of SAV such as turtle grass (*T. testudinum*) which can be outcompeted by shoal grass at lower salinities (Lirman and Cropper 2003).

The revised flow target improves the area in which the percent time in the Optimum Salinity Envelope for oysters is met 80–100% of the time approximately 2–3 km further downstream, and 2–3 km upstream relative to the 2007 Salinity Envelope flow targets (**Figure 10**; right maps). Previously, the area on either side of Cape Coral did not exceed 80% of time within the

DRAFT

envelope, whereas with the revised flow targets, this area increases to 80–100% of time. Oysters at the Iona Cove monitoring site (slightly upstream of Shell Point; **Figure 10**; right maps) improved from the 60–80% range to the 80–100% range of time within the Optimum Salinity Envelope.

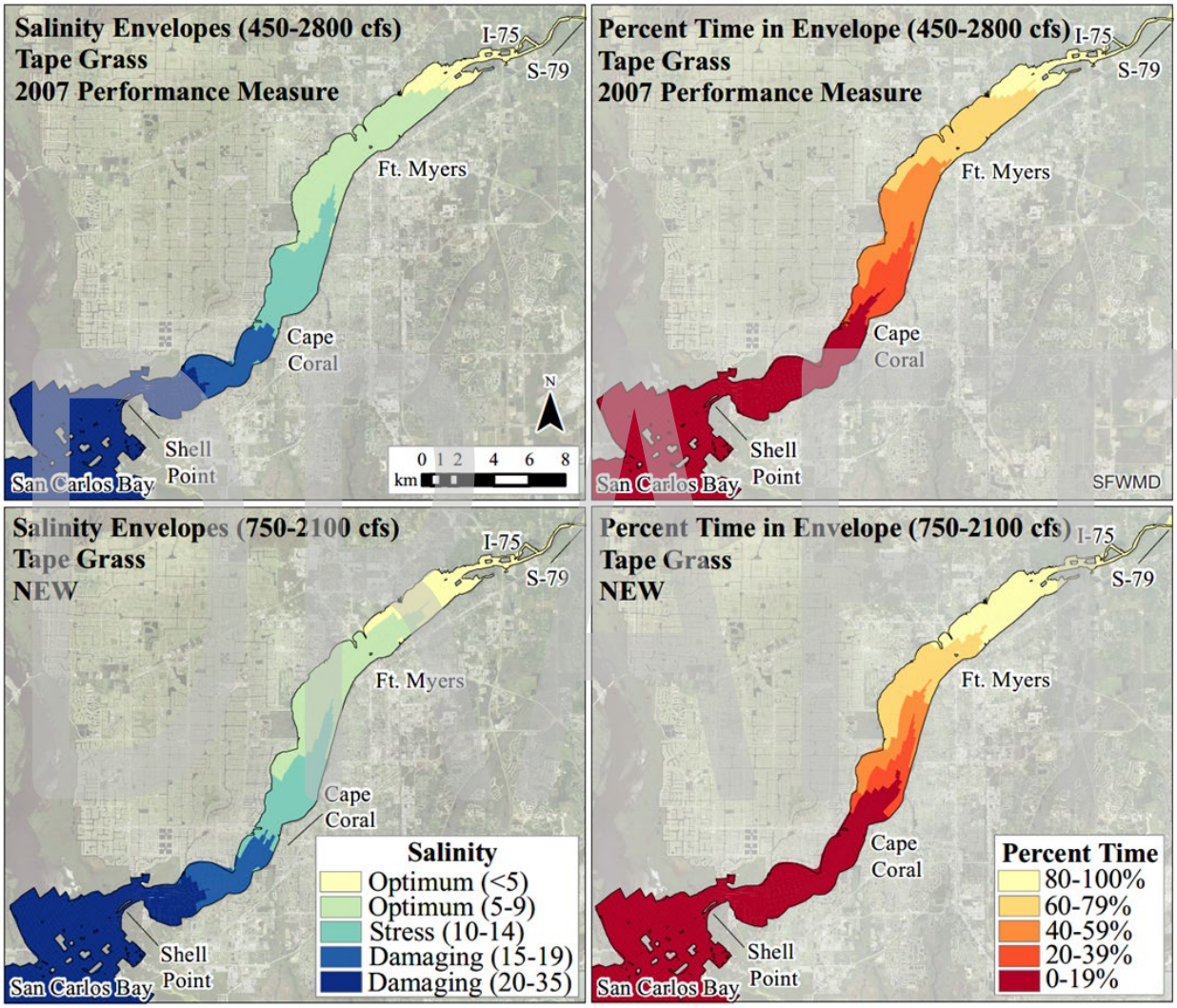

***Figure 8**. Mean salinity and percent time within Optimum Salinity Envelope for tape grass (salinities <10) in the Caloosahatchee River Estuary modeled on target flows from the 2007 PM (450–2800 cfs) and the new, revised PM (750–2100 cfs). With the revised flow target, salinity in the range of 0–5 increases further downstream, and the percent of time within the Optimum Salinity Envelope for tape grass improves to 80–100% of time to Ft. Myers.*

Note that the area in San Carlos Bay with salinities >25 influence the low percent time within the Optimum Salinity Envelope for oysters. Salinity >25 is deemed Stressful to oysters due to potential increased prevalence of Dermo infection, and increased likelihood of exposure to marine predators and pests (La Peyre et al. 2003; Barnes et al. 2010; Carroll et al. 2015; Kimbro et al. 2017; RECOVER 2019). However, the influence of Dermo may be limited in the CRE due

to the subtropical climate and seasonality, where temperature is low when salinity is high in the dry season, and temperature is high when salinity is low in the wet season (SFWMD 2020b).

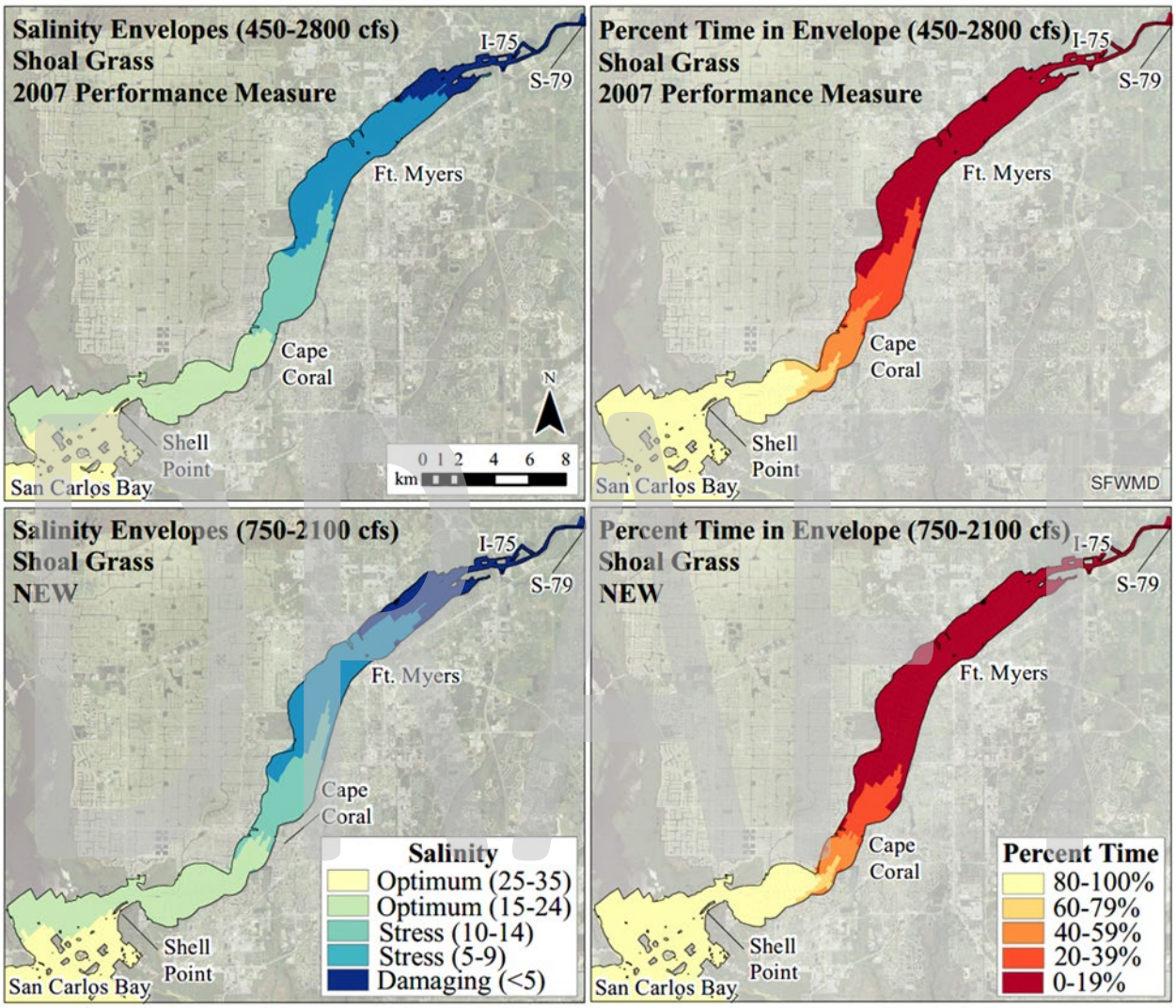

***Figure 9**. Mean salinity and percent time within Optimum Salinity Envelope for shoal grass (salinities 15–45) in the Caloosahatchee River Estuary modeled on target flows from the 2007 PM (450–2800 cfs) and the new, revised PM (750–2100 cfs). With the revised flow target, percent time within Optimum Salinity Envelope for shoal grass improves slightly upstream of the previous extent of the 2007 PM targets.*

The lowest densities of oysters are usually found at the Kitchel Key site, south of Shell Point in the area in which the percent time in the Optimum Salinity Envelope is <20% (**Figure 10**; left maps). Comparatively, Bird Island average oyster density was 1000–3000 per m^2 from 2012–2017 (RECOVER 2019), where salinities tend to be within the Optimum range (salinity 20–25) at least 60% of the time, and improvement compared to the 2007 Salinity Envelope PM targets (40–59% of time).

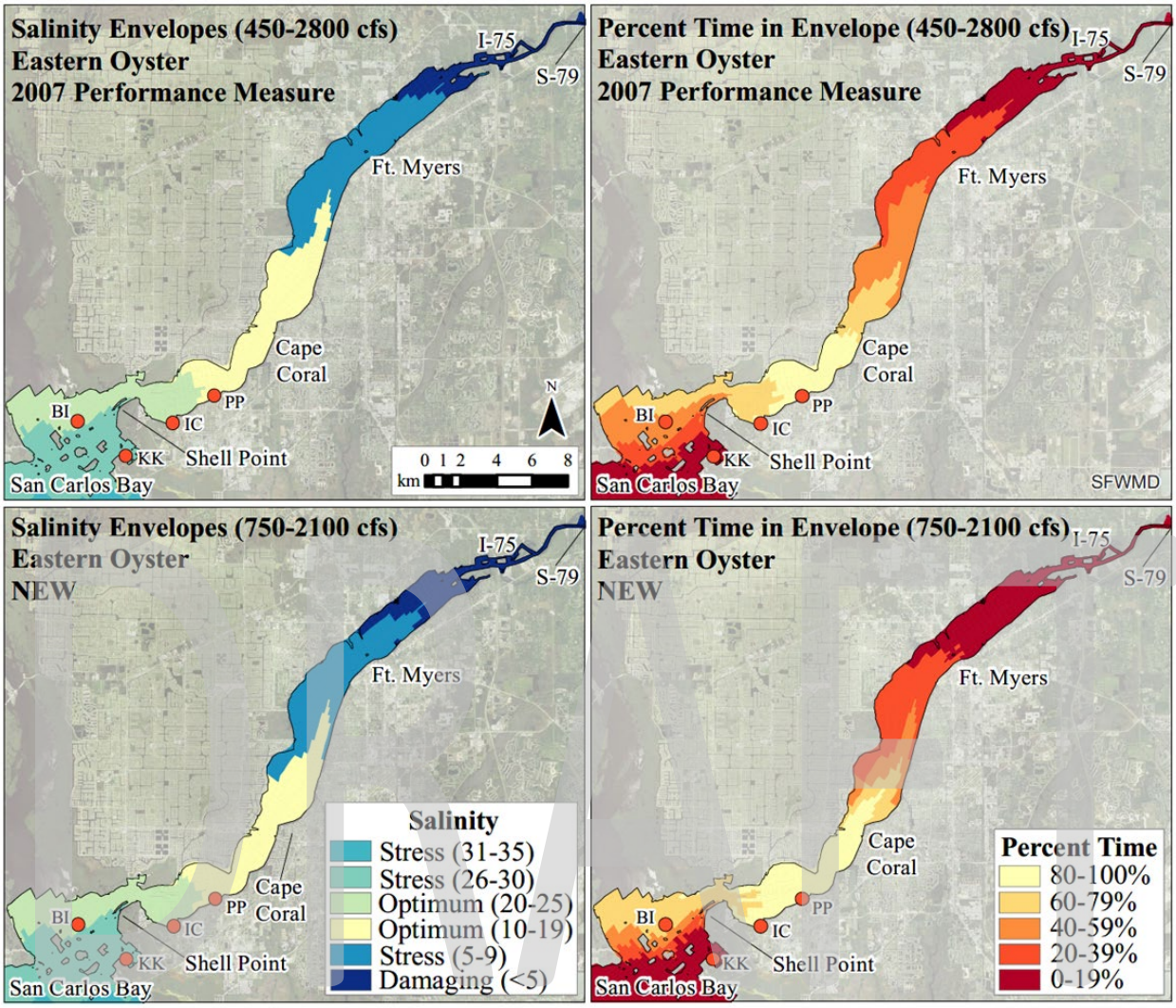

***Figure 10**. Mean salinity and percent time within Optimum Salinity Envelope for Eastern oyster (salinities 10–25) in the Caloosahatchee River Estuary modeled on target flows from the 2007 PM (450–2800 cfs) and the new, revised PM (750–2100 cfs). Red circles indicate RECOVER oyster monitoring sites from upstream to downstream: PP – Peppertree Point; IC – Iona Cove; BI – Bird Island; and KK – Kitchel Key. With the revised flow target, percent time within the Optimum Salinity Envelope for oysters improves in the optimum range ~2–3 km downstream, and ~2–3 km upstream of the previous extent.*

While the simulations are based on long-term means, high inflows and low salinity caused by extreme weather events can adversely affect oysters even further downstream: Iona Cove oysters were adversely affected by extreme low salinities (<2) in WY2014 and WY2017, in which little to no oysters were observed at monitoring sites (RECOVER 2019). The number of excursions outside the Optimum Salinity and Flow Envelopes are expected to decrease with CERP project implementation.

4.2 Stress and Damaging Flow Envelopes

4.2.1 Results: Discerning Stress Flows from Damaging Flows

The same modeling exercise was conducted for incremental ranges of flow greater than the Optimum Flow Envelope for the SLE and CRE. The manner in which Stress Flows and Damaging Flows were differentiated was based on resulting salinity maps where salinities were within the Stress Salinity Envelope and Damaging Salinity Envelope (**Table 1**), respectively. Areas where Stressful or Damaging Salinity Envelopes overlapped with RECOVER monitoring sites were noted. Where applicable, these sites are included in maps for **Figure 11**–**Figure 14**.

Stress Flow Envelopes range between the high flow bound of the Optimum Flow Envelope, and the low flow bound of the Damaging Flow Envelope. Generally, Damaging Flow Envelopes are described as flows greater than a specific flow volume.

4.2.1.1 Adverse Ecological Effects of Stress and Damaging Flow Envelopes >1400 cfs in the SLE

During Stress flows, different levels of stress for shoal grass begin in the middle estuary (salinities 10–14) and into the forks (salinities 5–9 halfway up the North and South Fork [**Figure 11**; left map]).

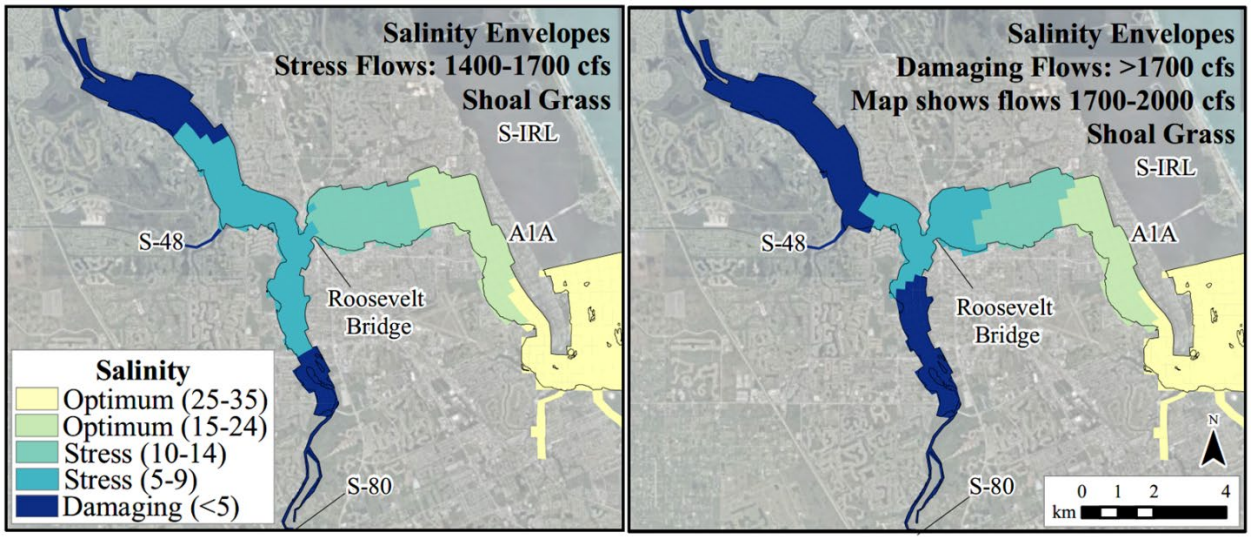

***Figure 11**. Mean salinity ranges in the SLE for shoal grass (Optimum Salinity Envelope 15–45) resulting from Stress Flows 1400–1700 cfs (left) and Damaging Flows >1700 (right; depicts salinities resulting from flow 1700–2000 cfs). Salinities fall into the Stress Salinity Envelope for shoal grass (5–14) with flows 1400–1700 cfs throughout much of the forks and middle estuary. Salinities fall within the Damaging Salinity Envelope for shoal grass (<5) with flows >1700 cfs throughout the North and South Fork, and increasingly stressful salinities into the middle estuary downstream of the US1 Roosevelt Bridge.*

Meanwhile, salinities in the SLE remain within the Optimum Salinity Envelope for shoal grass throughout most of the middle estuary and throughout the lower estuary, likely an effect of tidal

flushing. Salinities in the Optimum Salinity Envelope for Eastern oyster remain within the middle estuary where sites with the highest oyster densities are located, but salinities fall to 5–9 at the US1 Roosevelt Bridge and halfway through the Forks (**Figure 12**; left map). Damaging salinities <5 fall near the South Fork upstream extent for oysters and approximately 3 km downstream of the North Fork upstream extent for oysters.

During Damaging Flows, salinities in the range of 5–9 extends into the middle estuary, and salinities 10–14 extend nearly to A1A (**Figure 11**; right map). Salinities <5 was observed throughout most of the North and South Forks where they converge upstream of the US1 Roosevelt Bridge. Currently, shoal grass is not found through most of the estuary north of A1A; in the context of setting targets conducive to this species and other environmental factors such as suitable substrate and light availability were to improve, the resulting salinities described would certainly result in negative impacts to shoal grass. Conditions enter the Stress range in the middle estuary for oysters as salinities decrease into the range of 5–9, and conditions become damaging at salinities <5 throughout most of the Forks (**Figure 12**; right map). There are minimal changes downstream of A1A during either Stress Flows or Damaging Flows for oysters, likely due to tidal flushing; however, in the area downstream of A1A, oysters are not generally found in reefs, but rather peripheral habitats (e.g., intertidal dock pilings, seawalls, red mangrove [*Rhizophora mangle*] prop roots) because it is too sandy and water conditions are too turbulent for substrate stabilization.

DRAFT

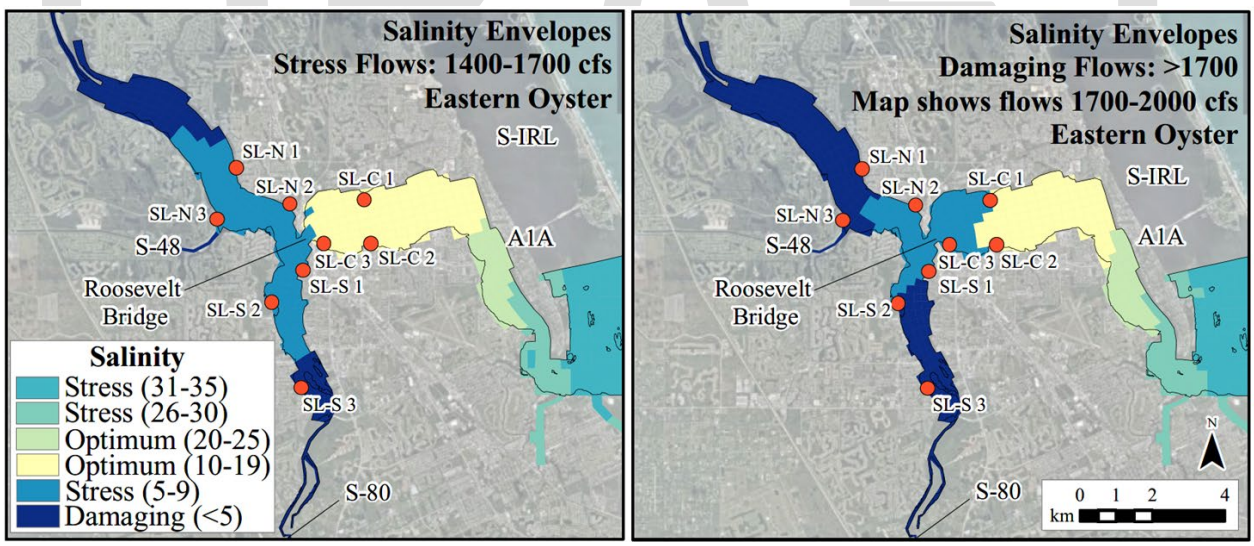

***Figure 12**. Mean salinity ranges in the SLE for Eastern oyster (Optimum Salinity Envelope 10–25) resulting from Stress Flows 1400–1700 cfs (left) and Damaging Flows >1700 (right; depicts salinities resulting from flow 1700–2000 cfs). Red circles indicate RECOVER oyster monitoring sites: St. Lucie North Fork sites (SL-N 1–3), St. Lucie South Fork sites (SL-S 1–3), and St. Lucie Central sites (SL-C 1–3). Salinities fall into the Stress Salinity Envelope for oysters (5–9) with flows 1400–1700 cfs throughout much of the forks but remain in the Optimum Salinity Envelope for oysters (10–25) in the middle estuary downstream past A1A. Salinities fall into the Damaging Salinity Envelope for oysters (<5) with flows >1700 cfs throughout much of the Forks, and stressful salinities (5–9) reach oyster reefs in the middle estuary.*

In **Figure 11** (right) and **Figure 12** (right), the salinity results are modeled flows ranging 1700–2000 cfs. The same trends apply to modeled flows 2000–2300 cfs: salinities are in the Damaging Salinity Envelope for both shoal grass and oysters throughout the Forks and in the Stress Salinity Envelope throughout the middle estuary to A1A. RECOVER oyster monitoring sites SL-N1 and SL-N3 enter the range for Damaging salinities <5 with flows 1700–2000 cfs, and in theory could be detectable via the monthly and quarterly monitoring; whereas in the range of 1400–1700 cfs, these oyster monitoring sites are still within Stressful, not Damaging, salinities ranging 5–9 (**Figure 12**; right map). Additional flows were modeled in iterations of several hundred cfs between 1700–3000 cfs, none of which caused Damaging salinities to move downstream of the US1 Roosevelt Bridge for either indicator species.

4.2.1.2 Adverse Ecological Effects of Stress and Damaging Flow Envelopes >2100 cfs in the CRE

Stress and Damaging Flow Envelopes as they are implemented here do not apply to tape grass, as the high flows create salinities <5 in large portions of the estuary, which is in the Optimum Salinity Envelope for this species. Therefore, the following Stress and Damaging Flow criteria is based upon shoal grass and oyster salinity tolerances only.

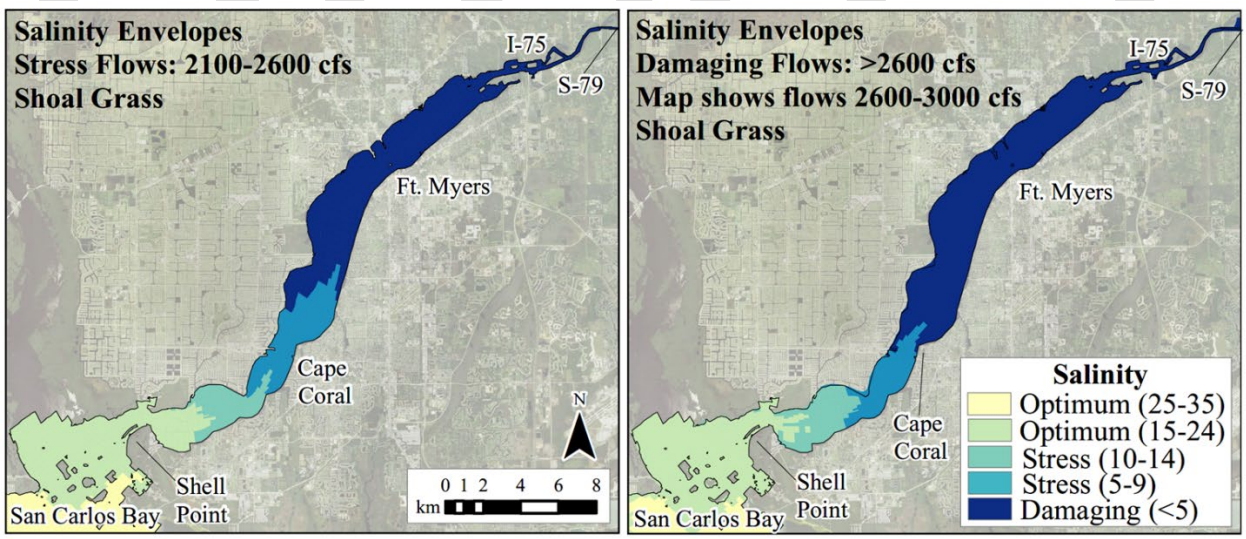

***Figure 13**. Mean salinity ranges in the CRE for shoal grass (Optimum Salinity Envelope 15–45) resulting from Stress Flows 2100–2600 cfs (left) and Damaging Flows >2600 (right; depicts salinities resulting from flow 2600–3000 cfs). Salinities fall into the Stress Salinity Envelope for shoal grass (5–14) with flows 2100–2600 cfs upstream and downstream of Cape Coral. Salinities fall into the Damaging Salinity Envelope for shoal grass (<5) with flows >2600 cfs throughout the entire upstream estuary to Cape Coral, and salinity ranging 5–9 creep into the lower estuary. While not depicted here, flows >3000 cfs will result in salinity 10–14 in limited areas of San Carlos Bay, which would be detrimental to other marine SAV species.*

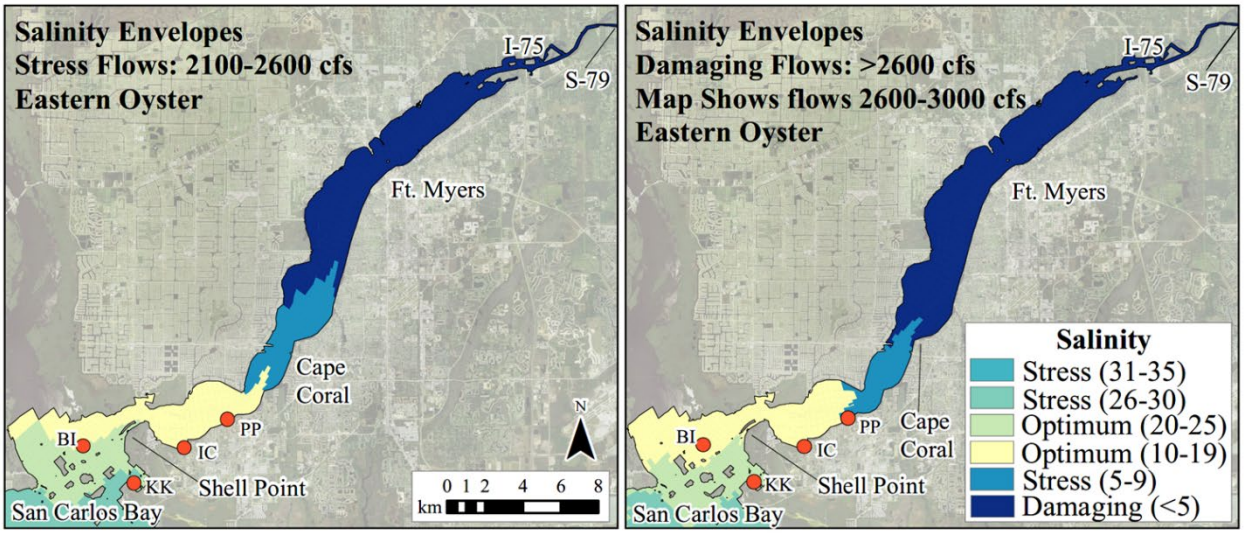

***Figure 14**. Mean salinity ranges in the CRE for Eastern oyster (Optimum Salinity Envelope 10–25) resulting from Stress Flows 1400–1700 cfs (left) and Damaging Flows >1700 (right; depicts salinities resulting from flow 1700–2000 cfs). Red circles indicate RECOVER oyster monitoring sites from upstream to downstream: PP – Peppertree Point; IC – Iona Cove; BI – Bird Island; and KK – Kitchel Key. Salinities fall into the Stress Salinity Envelope for oyster (5–9) with flows 2100–2600 cfs downstream of Cape Coral where the current known extent of oyster reefs are located. Salinities fall into the Damaging Salinity Envelope for oyster (<5) with flows >2600 cfs at Cape Coral, and salinity 5–9 reach further downstream all the way to monitoring site PP.*

The Stress Flow Envelope of 2100–2600 cfs affects shoal grass by causing a Stress Salinity Envelope in the range of 10–14 around the current upstream extent of this SAV in the CRE, and 5–9 approximately 2 km downstream and 4 km upstream of Cape Coral (**Figure 13**; left map). Oysters would not be affected approximately 2 km upstream of Peppertree Point, but Stress salinities ranging 5–9 would be found in proximity of Cape Coral, which is the approximate upstream extent for oysters in the CRE (**Figure 14**; left map). RECOVER monitoring sites in the CRE, except for Kitchel Key, remain within the Optimum Salinity Envelope.

During Damaging flows, salinities become highly Stressful for shoal grass in the range of 5–9, and remain within the Stress Salinity Envelope at salinities 10–14 near Shell Point (**Figure 13**; right map). Modeled flows >3000 cfs would cause salinities to decrease to 10–14 at a limited extent into San Carlos Bay. While tolerable to shoal grass for short periods, salinity in the range of 10–14 would negatively impact other marine SAV (e.g., turtle grass and manatee grass) and should be avoided. Oysters downstream of Cape Coral and into the lower estuary near the RECOVER monitoring sites at Peppertree Point would be exposed to Stress salinities ranging 5–9, and flows >4500 cfs would result in Stress salinities 5–9 at Iona Cove.

In generating Damaging Flows salinity maps for shoal grass (**Figure 13**; right map) and oysters (**Figure 14**; right map), the salinity results are modeled flows ranging 2600–3000 cfs. The same trends apply to modeled flows 3000–3400 cfs and 3400–3800 cfs: salinities occur in the Damaging Salinity Envelope for both shoal grass and oysters upstream of Cape Coral and in the Stress Salinity Envelope from Cape Coral to Peppertree. Additional flows were modeled in iterations of several hundred cfs between 2600–4800 cfs. The same trends resulted in the range

of 3800–4800 cfs, but flows >4800 cfs caused Stress salinities 5–9 at Iona Cove and Damaging salinities <5 near Peppertree Point.

4.3 Uncertainty

Uncertainty associated with the CH3D model validation of modeled versus observed salinity is very low (R^2 >0.9; Appendix A). However, there is a strong nonlinear relationship of flow and salinity in the estuaries: it's not a one-to-one relationship, despite general trends such as higher freshwater inflow resulting in lower salinity. Seasonal characteristics such as rainfall (i.e., wet season vs. dry season) and other contributing factors such as tides at the offshore boundary, and physical wind forces at the water surface, increases the complexity of this relationship.

These flow-salinity simulations include the long-term mean, but extreme levels of rainfall caused by tropical storms, hurricanes, and conditions associated with El Niño can have deleterious effects on short-term timescales of days-to-weeks in the Stress and Damaging Salinity Envelopes (**Table 1**). CERP aims to address these excursion events with project implementation and updated operational plans. Therefore, it is expected that there will be a reduction in number of these excursion events.

Future modeling within the context of refined end-state targets will better define Salinity Envelope targets in terms of duration, return frequency, seasonality, and appropriate salinity ranges (Appendix C). Ongoing mesocosm studies and predictive, mechanistic ecological model development are anticipated key data sets and tools which can be used to refine targets in future PM updates (Appendix C).

Uncertainty regarding climate change, sea level rise, and increases in sea surface temperature is high and should be explicitly addressed in future simulation and predictive modeling tools used for the development of PMs and evaluation protocols (Appendix C).

5 SCIENTIFIC BASIS: RECOVER MONITORING AND ASSESSMENT PLAN

5.1 MAP Module

See CERP Monitoring and Assessment Plan: Part 1 Monitoring and Supporting Research - Northern Estuaries Module section 3.3.3.1 and South Florida Hydrology Monitoring Network Module section 3.5.3.3 (RECOVER 2004a) for the original MAP monitoring. The MAP was updated in 2009 and the most current Northern Estuaries section can be found in the CERP MAP 2009 Northern Estuaries Module Section 3.2.3 (RECOVER 2009).

5.2 Assessment Approach

MAP monitoring includes oyster, SAV, and benthic infauna (RECOVER 2009; RECOVER 2019). Temperature and salinity data are routinely included in the monitoring. Systematic, long-term ecological data are needed in addition to systematic, long-term monitoring of salinity, temperature, and light attenuation to conduct assessments and validate models or refine model parameters. Evaluation tools include the graphical displays of data, as well as the results of Habitat Suitability Index (HSI) models that will determine habitat unit changes for the base

DRAFT

conditions and the final selected alternative. Future Evaluation and Assessment tools should be developed as additional Performance Measures (Appendix C).

5.3 Conceptual Ecological Models

Conceptual Ecological Models (CEM) for the Northern Estuaries are described in Sime (2005), VanArman (2005), Barnes (2005), and Crigger et al. (2005). These CEMs have been refined over time to focus on stressors that can be influenced by CERP and other active restoration efforts (RECOVER 2006a, 2006b). Regional CEMs and hypothesis clusters are currently being updated with a completion date of 2020.

<u>Regional CEMs (2005)</u>
St. Lucie Estuary and Southern Indian River Lagoon, Loxahatchee River and Estuary, Caloosahatchee River Estuary, Lake Worth Lagoon

<u>Hypothesis Clusters (2009)</u>
Northern Estuaries (NE) Oyster Health and Abundance, NE SAV, NE Benthic Infaunal Invertebrates, NE Fisheries

6 NOTES

This Performance Measure supersedes and addresses Northern Estuaries Salinity Envelope (Last Date Revised: April 2007), NE-1 St. Lucie Estuary Salinity Envelope (Last Date Revised: September 2005), NE-2 Lake Worth Lagoon Salinity Envelope, NE-3 Caloosahatchee Estuary Salinity Envelope, and Loxahatchee River Estuary Salinity Envelope (all Last Date Revised: September 2005).

The 2007 Northern Estuaries Salinity Envelope PM was modified per the following:

- Modeling flow-salinity relationships was conducted with the CH3D Hydrodynamic Salinity Model.
- In addition to identifying flow targets based on Optimum Salinity Envelope to Northern Estuaries' indicator species for the purpose of maintaining a healthy estuarine ecosystem, Stress and Damaging Salinity Envelopes for individual indicator species were also defined. Modeled Flow Envelope alternatives and their resulting salinities were assessed to set a target Optimum, Stress, and Damaging Flow Envelopes for each indicator species in the SLE and CRE.
- Rather than develop targets based on a single location in the estuary (e.g., the 2007 PM included targets that set salinities in an optimum range at the US1 Roosevelt Bridge in the SLE), a spatially-explicit approach assessing salinities throughout the entire SLE and CRE, as well as downstream conditions was implemented by comparing salinity gradient maps and maps which represent percent time within the Optimum Salinity Envelope. Model simulations were based on a 50-year period of record of observed flows and salinity measurements.
- Coordination with the Interagency Modeling Center ensured that the Optimum Flow Envelopes are sensitive enough to detect changes in hydrology per the implementation of

DRAFT

new infrastructure and operations, and several future scenarios that will include the implementation of key CERP projects (Appendix B).

- The 2007 PM for the SLE was adjusted from 350–2000 cfs to an Optimum Flow Envelope of 150–1400 cfs. Both the low and high flow bounds were reduced compared to the 2007 PM targets in order to increase salinities in the estuary proper, which, especially in the forks, were insufficiently low. This could provide significant benefit to extant Eastern oyster reefs upstream by creating Optimum salinities throughout middle estuary and both Forks.
- The 2007 PM for the CRE was adjusted from 450–2800 cfs to an Optimum Flow Envelope of 750–2100 cfs. The low flow bound was raised from 450 cfs to 750 cfs. A recent update to the CRE Minimum Flows and Levels determined a threshold of 457 cfs to prevent significant harm to the estuary (SFWMD 2020b). For setting flow targets conducive to supporting healthy estuarine systems, 450 cfs was assumed too low for the purposes of this PM. The new low flow bound target of 750 cfs as should improve salinities in the upstream CRE for tape grass habitat. The high flow bound was reduced from 2800 cfs to 2100 cfs to reduce the impact of lower salinity downstream for shoal grass and oysters. For more information on the CRE MFL rule, please see SFWMD (2020b).
- Additional modeling is needed to determine impacts of SLE Damaging Flows to the S-IRL.
- Flow targets for the LRE are based on the 2006 Restoration Plan for the Northwest Fork of the Loxahatchee River (Restoration Plan 2006). Flow-salinity relationships were reevaluated in 2011 and found to be consistent with the targets as outlined in the Restoration Plan (2006) (Addendum to the Restoration Plan 2012). An update for the LRE was not included in this PM revision.
- As of 2015, Lake Worth Lagoon is no longer included in the RECOVER Northern Estuaries Program. With the removal of the North Palm Beach project from the list of planned CERP Projects, it was determined that the remaining planned projects will not have any anticipated impacts on Lake Worth Lagoon that would require evaluation and assessment of project alternative on this system.

7 NORTHERN ESTUARIES WORKING GROUP

Phyllis A. Klarmann, SFWMD
Detong Sun, SFWMD
Amanda Kahn, SFWMD
Patricia Gorman, SFWMD
Gretchen Ehlinger, USACE
Ramon Martin, USFWS

Additional thanks to the following who provided important information, literature, and constructive feedback during the formulation of this Performance Measure update:

Michael C. Brown, SFWMD
Harold Hennessey-Correa, SFWMD
Walter Wilcox, SFWMD

DRAFT

Melanie Parker, FFWCC FWRI
Barbara Welch, SFWMD
Zhiqiang Chen, SFWMD
Lori Morris, St. Johns River Water Management District (SJRWMD)
Robert Chamberlain, SJRWMD
Peter Doering, SFWMD retired
Patrick Pitts, USFWS retired

8 LITERATURE CITED

Addendum to the Restoration Plan for the Northwest Fork of the Loxahatchee River. 2012. South Florida Water Management District, West Palm Beach, FL, Florida Department of Environmental Protection, Hobe Sound, FL, and Loxahatchee River District, Jupiter, FL: 507pp.

Barnes, T. 2005. Caloosahatchee Estuary Conceptual Ecological Model. Wetlands 25(4): 884–897.

Barnes, B.B., M.W. Luckenbach, and P.R. Kingsley-Smith. 2010. Oyster reef community interactions: The effect of resident fauna on oyster (*Crassostrea* spp.) larval recruitment. Journal of Experimental Marine Biology and Ecology 391: 169–177.

Burd, A. B., and K.H. Dunton. 2001. Field verification of a light-driven model of biomass changes in the seagrass *Halodule wrightii*. Marine Ecology Progress Series 209: 85–98.

Buzzelli, C., Z. Chen, T. Coley, P. Doering, R. Samimy, D. Schlesinger, and B. Howes. 2013a. Dry season sediment-water exchanges of nutrients and oxygen in two Floridian estuaries: Patterns, comparisons, and internal loading. Florida Scientist 76(1): 54–79.

Buzzelli, C., P. Doering, Y. Wan, and J. Boyer. 2013b. Seasonal dissolved inorganic nitrogen and phosphorus budgets for two sub-tropical estuaries in South Florida. Biogeosciences 10: 6721–6736.

Buzzelli, C., P. Doering, Y. Wan, and D. Sun. 2014. Modeling ecosystem processes with variable freshwater inflow to the Caloosahatchee River Estuary, southwest Florida. II. Nutrient loading, submarine light, and seagrasses. Estuarine, Coastal and Shelf Science 151: 272–284.

Cake, E.W. 1983. Habitat Suitability Index Models: Gulf of Mexico American Oyster. US Fish & Wildlife Service Report No. FWS/OBS-82/10.57, Washington, D.C.

Carroll, J.M., K.A. O'Shaughnessy, G.A. Dietrich, and C.M. Finelli. 2015. Are oysters being bored to death? Influence of *Cliona celata* on *Crassostrea virginica* condition, growth, and survival. Diseases of Aquatic Organisms 117: 31–44.

Casas, S.M., R. Lavaud, M.K. La Peyre, L.A. Comeau, R. Filgueira, and J.F. La Peyre. 2018. Quantifying salinity and season effects on eastern oyster clearance and oxygen consumption rates. Marine Biology 165(90): 1–13.

DRAFT

Chen, Z., P.H. Doering, M. Ashton, and B.A. Orlando. 2014. Mixing behavior of colored dissolved organic matter and its potential ecological implication in the Caloosahatchee River Estuary, Florida. Estuaries and Coasts 38(5): 1706–1718.

Chen, Z., and P.H. Doering. 2016. Variation of light attenuation and the relative contribution of water quality constituents in the Caloosahatchee River Estuary. Florida Scientist 79(2/3): 93-108.

Crigger, D.K., Graves, G.A., and D.L. Fike. 2005. Lake Worth Lagoon conceptual ecological model. Wetlands 25(4): 943–954.

Czerny, A.B., and K.H. Dunton. 1995. The effects of in situ light reduction on the growth of two subtropical seagrasses, *Thalassia testudinum* and *Halodule wrightii*. Estuaries 18: 418–427.

Dickinson, G.H., A.V. Ivanina, O.B. Matoo, H.O. Portner, G. Lannig, C. Bock, E. Beniash, and I.M. Sokolova. 2012. Interactive effects of salinity and elevated CO2 levels on juvenile eastern oysters, *Crassostrea virginica*. The Journal of Experimental Biology 215: 29–43.

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

Doering, P.H., and R.H. Chamberlain. 1999. Water quality and the source of freshwater discharge to the Caloosahatchee Estuary, FL. Water Resources Bulletin 35: 793–806.

Doering, P.H., R.H. Chamberlain, and D.E. Haunert. 2002. Using Submerged Aquatic Vegetation to Establish Minimum and Maximum Freshwater Inflows to the Caloosahatchee Estuary, Florida. Estuaries 25(6B): 1343–1354.

Dunton, K.H. 1990. Production ecology of *Ruppia maritima* L. s.l. and *Halodule wrightii* Ashers. in two subtropical estuaries. Journal of Experimental Marine Biology and Ecology 143: 147–164.

Frankovich, T.A., Morrison, D., and J.W. Fourqurean. 2011. Benthic Macrophyte Distribution and Abundance in Estuarine Mangrove Lakes and Estuaries: Relationships to Environmental Variables. Estuaries and Coasts 34(1): 20–31.

FWRI. 2018. Oyster monitoring in the northern estuaries on the southeast and southwest coasts of Florida. 2017 Annual Report. Prepared for the South Florida Water Management District, West Palm Beach, FL.

Galtsoff, P.S. 1964. The American oyster *Crassostrea virginica* Gmelin. U.S. Fisheries Bulletin 64: 1–480.

Heilmayer, O., J. Digialleonardo, L. Qian, and G. Roesijadi. 2008. Stress tolerance of a subtropical *Crassostrea virginica* population to the combined effects of temperature and salinity. Estuarine, Coastal and Shelf Science 79: 179–185.

DRAFT

Jacoby, C. 2012. Appendix 9.E. Response of *Vallisneria americana* following repeated exposure to different salinity regimes. In: Lowe, E.F., L.E. Battoe, H. Wilkening, M. Cullum, and T. Bartol. (Eds.) 2012. St. Johns River Water Supply Impact Study. Technical Publication SJ2012-1. St. Johns River Water Management District, Palatka, Florida.

Jarvis, J., and K.A. Moore. 2008. Influence of environmental factors on *Vallisneria americana* seed germination. Aquatic Botany 88(4): 283–294.

Ji, Z.G., G. Hu, J. Shen, and Y. Wan. 2007. Three-dimensional modeling of hydrodynamics processes in the St. Lucie Estuary. Estuarine, Coastal, & Shelf Science 73: 188–200.

Johns, N.D. 2012. Examining Bay Salinity Patterns and Limits to *Rangia cuneata* Populations in Texas Estuaries. National Wildlife Federation, Austin, Texas. Texas Water Development Board Contract Report Number 1148311236.

Kimbro, D.L., J.W. White, H. Tillotson, N. Cox, M. Christopher, O. Stokes-Cawley, S. Yuan, T.J. Pusack, and C.D. Stallings. 2017. Local and regional stressors interact to drive a salinization-induced outbreak of predators on oyster reefs. Ecosphere 8(11): e01992. 10.1002/ecs2.1992

Kenworthy, W.J., and M.S. Fonseca. 1996. Light requirements of seagrasses *Halodule wrightii* and *Syringodium filiforme* derived from the relationship between diffuse light attenuation and maximum depth distribution. Estuaries 19: 740–750.

Koch, M.S., S.A. Schopmeyer, C. Kyhn-Hansen, C.J. Madden, and J.S. Peters. 2007. Tropical seagrass species tolerance to hypersalinity stress. Aquatic Botany 86: 14-24.

Kraemer, G.P., R.H. Chamberlain, P.H. Doering, A.D. Steinman, and M.D. Hanisak. 1999. Physiological Responses of the Freshwater Angiosperm *Vallisneria americana* along a Salinity Gradient in the Caloosahatchee Estuary (Southwestern Florida). Estuaries 22(1): 138–148.

La Peyre, M.K., A.D. Nickens, A.K. Volety, G.S. Tolley, and J.F. La Peyre. 2003. Environmental Significance of freshets in reducing *Perkinsus marinus* infection in eastern oysters *Crassostrea virginica*: potential management implications. Marine Ecology Press Series 248: 165–176.

La Peyre, M.K., B. Gossman, and J.F. La Peyre. 2009. Defining Optimal Flow for Oyster Production: Effects of Freshet Rate and Magnitude of Change and Duration on Eastern Oysters and *Perkinsus marinus* Infection. Estuaries and Coasts 32: 522–534

Lauer, Nathan, M. Yeager, A.E. Kahn, D.R. Dobberfuhl, and C. Ross. 2011. The effects of short term salinity exposure on the sublethal stress response of *Vallisneria americana* Michx (Hydrocharitaceae). Aquatic botany 95(3): 207–213.

DRAFT

Lirman, D., and W.P. Cropper, Jr. 2003. The Influence of Salinity on Seagrass Growth, Survivorship, and Distribution within Biscayne Bay, Florida: Field, Experimental, and Modeling Studies. Estuaries 26(1): 131-141.

Lowe, M.R., T. Sehlinger, T.M. Soniat, and M.K. La Peyre. 2017. Interactive Effects of Water Temperature and Salinity on Growth and Mortality of Eastern Oysters, *Crassostrea virginica*: A Meta-Analysis Using 40 Years of Monitoring Data. Journal of Shellfish Research 36(3): 683–697.

Lu, L., J. Grant, and J. Barrell. 2008. Macrofaunal Spatial Patterns in Relationship to Environmental Variables in the Richibucto Estuary, New Brunswick, Canada. Estuaries and Coasts 31: 994–1005.

MacKenzie, Jr., C.L. 2007. Causes Underlying the Historical Decline in Eastern Oyster (*Crassostrea virginica* Gmelin, 1791) Landings. Journal of Shellfish Research 26(4): 927–938.

McMahan, C.A. 1968. Biomass and Salinity Tolerance of Shoalgrass and Manateegrass in Lower Laguna Madre, Texas. The Journal of Wildlife Management 32(3): 501–506.

Oscar, M.A., S. Barak, and G. Winters. 2018. The Tropical Invasive Seagrass, *Halophila stipulacea*, Has a Superior Ability to Tolerate Dynamic Changes in Salinity Levels Compared to Its Freshwater Relative, *Vallisneria americana*. Frontiers in Plant Science, 9: 950. doi: 10.3389/fpls.2018.00950

Parker, M.L., W.S. Arnold, S.P. Geiger, P. Gorman, and E.H. Leone. 2013. Impacts of Freshwater Management Activities on Eastern Oyster (*Crassostrea virginica*) Density and Recruitment: Recovery and Long-Term Stability in Seven Florida Estuaries. Journal of Shellfish Research 32(3): 695–708.

Parker, M.L., and R. Radigan. 2018. Oyster monitoring in the Northern Estuaries on the southeast and southwest coasts of Florida. 2017 Annual Report. Submitted to the South Florida Water Management District.

RECOVER. 2004. Draft Conceptual Ecological Models. In: RECOVER. CERP Monitoring and Assessment Plan: Part 1 Monitoring and Supporting Research, Restoration Coordination and Verification Program, c/o United States Army Corps of Engineers, Jacksonville District, Jacksonville, Florida, and South Florida Water Management District, West Palm Beach, Florida, Appendix A.

RECOVER 2006a. CERP Monitoring and Assessment Plan (MAP): Part 2 2006 Assessment Strategy for the MAP. Restoration Coordination and Verification. US Army Corps of Engineers, Jacksonville District, Jacksonville, FL and South Florida Water Management District, West Palm Beach FL.

RECOVER. 2006b. Comprehensive Everglades Restoration Plan Adaptive Management Strategy. Restoration Coordination and Verification, US Army Corps of

DRAFT

Engineers, Jacksonville, FL, and South Florida Water Management District, West Palm Beach, FL. April 2006.

RECOVER. 2007a. Northern Estuaries Performance Measure, Salinity Envelopes Documentation Sheet, April 2007. Restoration Coordination and Verification, c/o U.S. Army Corps of Engineers, Jacksonville District, Jacksonville, FL, and South Florida Water Management District, West Palm Beach, FL: 26pp.

RECOVER. 2007b. Northern Estuaries Performance Measure, Oyster Habitat Documentation Sheet, March 2007. Restoration Coordination and Verification, c/o U.S. Army Corps of Engineers, Jacksonville District, Jacksonville, FL, and South Florida Water Management District, West Palm Beach, FL: 9pp.

RECOVER. 2007c. Northern Estuaries Performance Measure, Submerged Aquatic Vegetation Documentation Sheet, March 2007. Restoration Coordination and Verification, c/o U.S. Army Corps of Engineers, Jacksonville District, Jacksonville, FL, and South Florida Water Management District, West Palm Beach, FL: 20pp.

RECOVER. 2009. CERP Monitoring and Assessment Plan. Restoration Coordination and Verification, c/o U.S. Army Corps of Engineers, Jacksonville District, Jacksonville, FL, and South Florida Water Management District, West Palm Beach, FL: 156pp.

RECOVER. 2012. Southern Coastal Systems Performance Measure, Salinity in Florida Bay Documentation Sheet, June 2012. Restoration Coordination and Verification, c/o U.S. Army Corps of Engineers, Jacksonville District, Jacksonville, FL, and South Florida Water Management District, West Palm Beach, FL: 20pp.

RECOVER. 2017. Southern Coastal Systems Performance Measure, Juvenile Spotted Seatrout Habitat Quality, February 2017. Restoration Coordination and Verification, c/o U.S. Army Corps of Engineers, Jacksonville District, Jacksonville, FL, and South Florida Water Management District, West Palm Beach, FL: 21pp.

RECOVER. 2019. 2019 Everglades System Status Report. Assessment period of 2012–2017. Restoration Coordination and Verification, c/o U.S. Army Corps of Engineers, Jacksonville District, Jacksonville, FL, and South Florida Water Management District, West Palm Beach, FL: 202pp.

Restoration Plan for the Northwest Fork of the Loxahatchee River. 2006. South Florida Water Management District, West Palm Beach, FL: 469pp.

Rivera-Guzmán, N.E., P. Moreno- Casosola, S.E. Ibarra-Obando, V.J. Sosa, and J. Herrera-Silveira. 2014. Long term state of coastal lagoons in Veracruz, Mexico: Effects of land use changes in watershed on seagrasses habitats. Ocean & Coastal Management 87: 30–39.

DRAFT

Salewski, E.A., and C.E. Proffitt. 2016. Separate and Combined Effects of Estuarine Stress Gradients and Disturbance on Oyster Population Development on Restored Reefs. Estuaries and Coasts 39: 510–528.

SFWMD. 2019. South Florida Environmental Report Chapter 8C: St. Lucie and Caloosahatchee River Watersheds Annual Report. South Florida Water Management District, West Palm Beach, FL: 44pp.

SFWMD. 2020a. South Florida Environmental Report Chapter 8C: St. Lucie and Caloosahatchee River Watersheds Annual Report. South Florida Water Management District, West Palm Beach, FL: 47pp.

SFWMD. 2020b. Technical Document to Support the Reevaluation of the Minimum Flow and Level Criteria for the Caloosahatchee River Estuary. Final Report. South Florida Water Management District, West Palm Beach, FL.

Shields, E.C., and K.A. Moore. 2016. Effects of sediment and salinity on the growth and competitive abilities of three submersed macrophytes. Aquatic Botany 132: 24–29.

Sime, P. 2005. St. Lucie Estuary and Indian River Lagoon Conceptual Ecological Model. Wetlands 25(4): 898–907.

Shumway, S.E. 2006. Natural environmental factors. In: Kennedy, V.S., R.I.E. Newell, and A.F. Eble (Eds.). The Eastern Oyster *Crassostrea virginica*. Maryland Sea Grant College Publication, College Park, Maryland: 467–513.

Stockley, N.D., Sullivan, J.M., Hanisak, D., and M.N. McFarland. 2018. Using observation networks to examine the impact of Lake Okeechobee discharges on the St. Lucie Estuary, Florida. In: Hou, W., and R.A. Arnone. (Eds.) Proceedings of the Society of Photo-Optical Instrumentation Engineers (SPIE) Ocean Sensing and Monitoring X. Volumbe 10631, International Society for Optics and Photonics, Bellingham, Washington. Page 1063109.

Tallerico, J., and D. Dobberfuhl. 2012. Appendix 9.D. Intensive Submerged Aquatic Vegetation Monitoring in the Lower St. Johns River Basin. In: Lowe, E.F., L.E. Battoe, H. Wilkening, M. Cullum, and T. Bartol. (Eds.) 2012. St. Johns River Water Supply Impact Study. Technical Publication SJ2012-1. St. Johns River Water Management District, Palatka, Florida.

Twilley, R. R., and Barko, J. W. (1990). The growth of submersed macrophytes under experimental salinity and light conditions. Estuaries 13(3): 311–321.

Unesco. 1981. Tenth report of the joint panel on oceanographic tables and standards. Unesco Technical Papers in Marine Science (36): 28 pp.

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

DRAFT

Volety, A.K., S.G. Tolley, and J.T. Winstead. 2003. Effects of seasonal and water quality parameters on oysters (*Crassostrea virginica*) and associated fish populations in the Caloosahatchee River. Interpretive Report (Award #C-12412-A1) Submitted to the South Florida Water Management District.

Volety, A.K., M. Savarese, S.G. Tolley, W.S. Arnold, P. Sime, P. Goodman, R.H. Chamberlain, and P.H. Doering. 2009. Eastern oysters (*Crassostrea virginica*) as an indicator for restoration of Everglades Ecosystems. Ecological Indicators 9s: S120–S136.

Wilson, C., L. Scotto, J. Scarpa, A. Volety, S. Laramore, and D. Haunert. 2005. Survey of Water Quality, Oyster Reproduction, and Oyster Health Status in the St. Lucie Estuary. Journal of Shellfish Research 24(1): 157–165.

Zieman, J.C., and R.T. Zieman. 1989. The ecology of the seagrass meadows of the west coast of Florida: a community profile. U.S. Fish and Wildlife Service Biological Reports 85(7.25): 155 pp.

DRAFT