RECOVER Northern Estuaries Performance Measure: Salinity Envelope

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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 51-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 (ma) flows over the 51-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 ma flow periods in the Stress Flow Envelope (three or more consecutive events would reflect >1 month of stressful salinities), and no more than one (1) consecutive 14-day ma flow periods in

the Damaging Flow Envelope (two consecutive events would reflect ~1 month of damaging salinities) in either the SLE or CRE.

More Optimum 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.

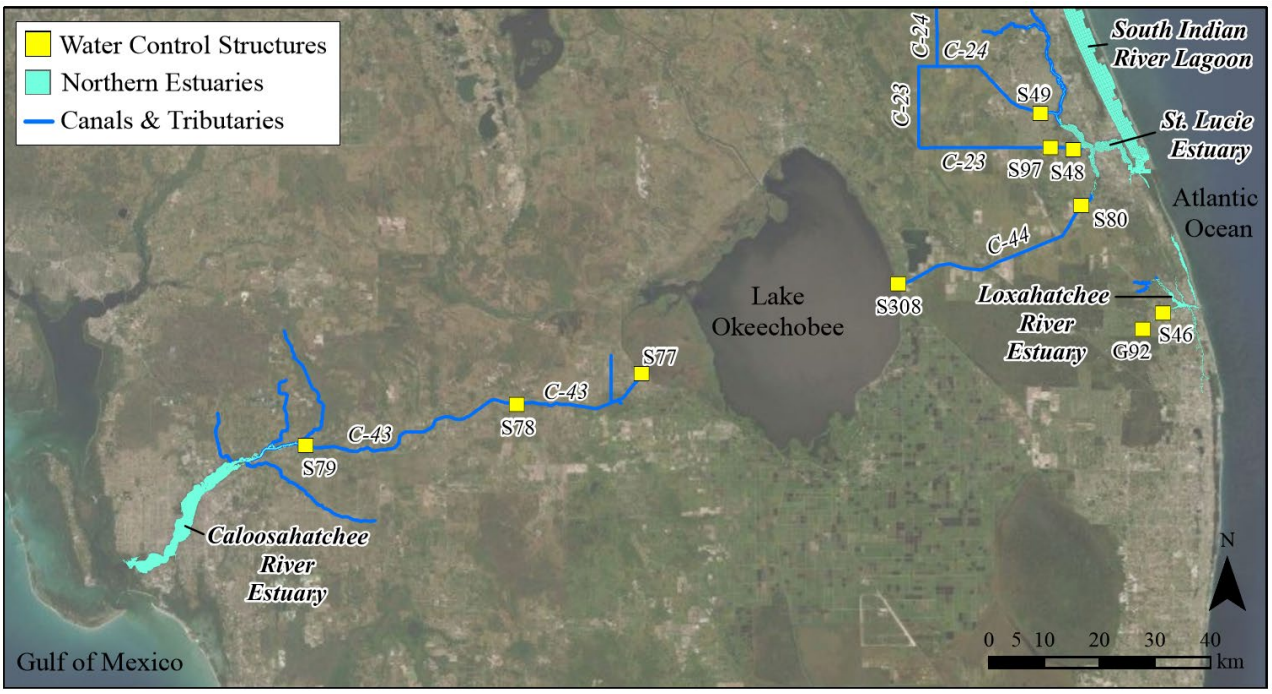

***Figure 1**. The Caloosahatchee, St. Lucie, and Loxahatchee Estuaries relative to Lake Okeechobee and the greater Everglades ecosystem*

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 Florida Project (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 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.

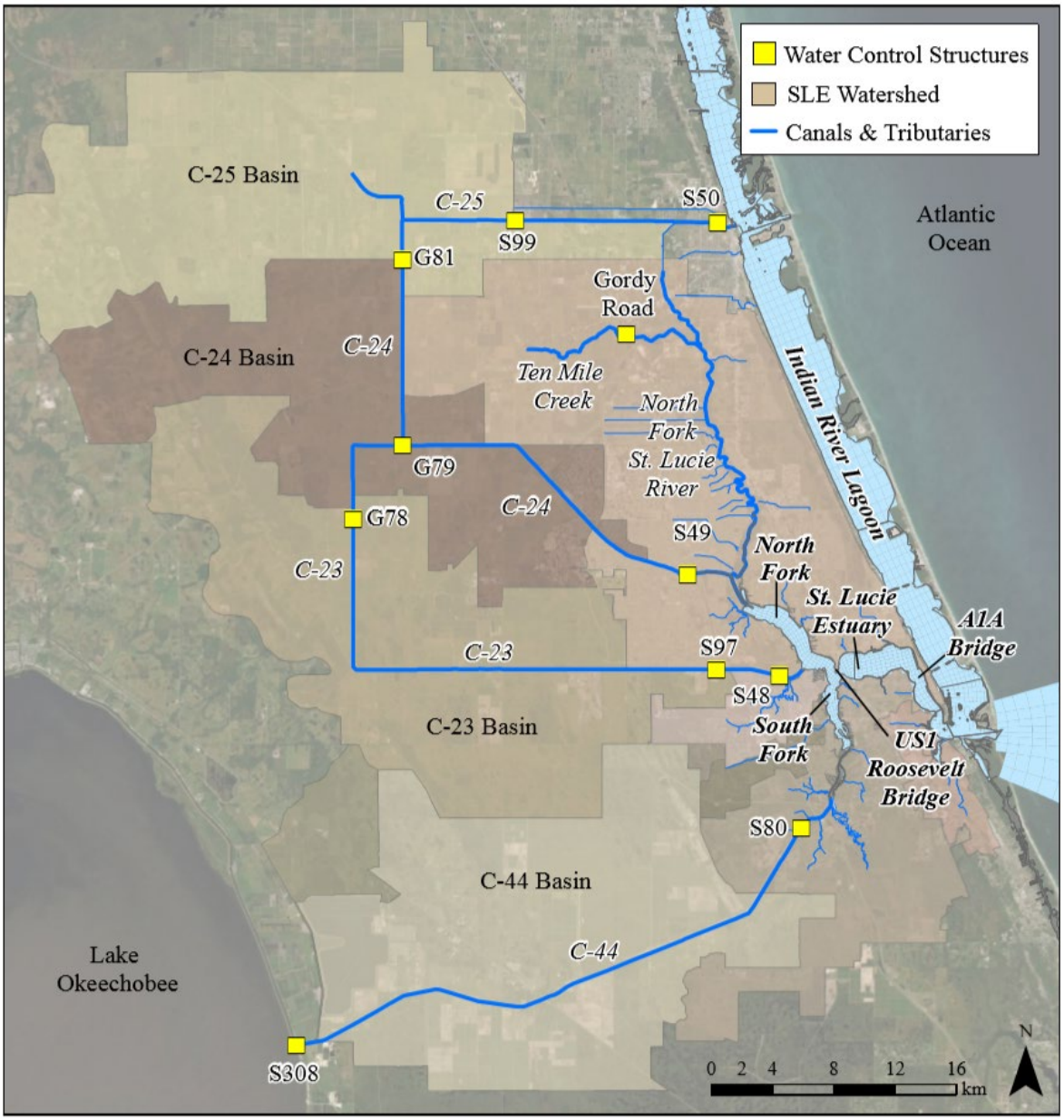

***Figure 2**. The St. Lucie Estuary relative to proximity to major waterbodies and sources of inflow*

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 (ma); and
- 28 local basin flow events >2000 cfs over 14-day ma.

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).

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.

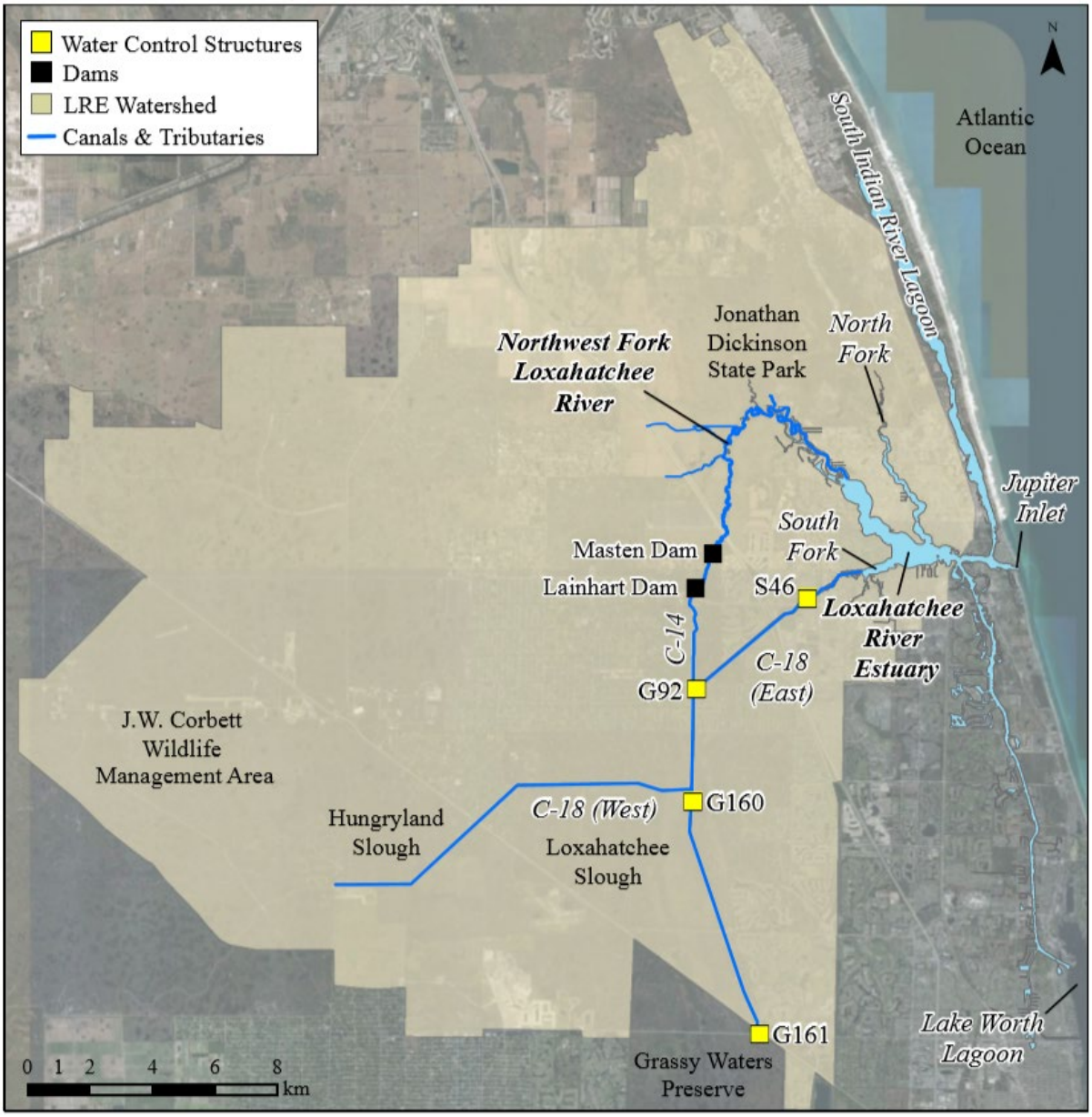

***Figure 3**. The LRE and major tributaries including the Northwest Fork*

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).

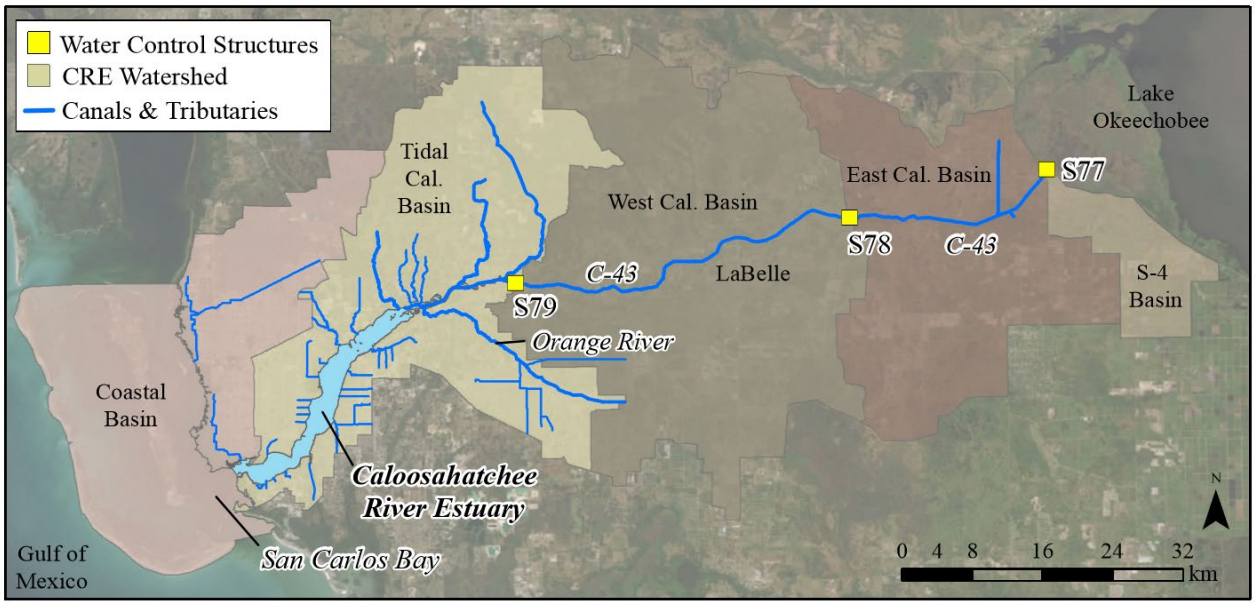

***Figure 4**. The CRE relative to its proximity to major waterbodies and sources of inflow*

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 [F.A.C.]).

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; and landscape alterations including the expansion of watersheds and connection to Lake Okeechobee make historical reference-based restoration goals problematic, and further complicated by uncertainties surrounding climate change and how water management (for people and environment) will need to adapt. For example, the RECOVER PM for salinity in Florida Bay 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 historical dataset for the Northern Estuaries commensurate with that for Florida Bay. Additionally, the multiple demands on water resources as previously described requires a holistic approach that uses both scientific and policy-based solutions that are equitable for all users. Many of these considerations are beyond the scope of this single RECOVER PM.

Therefore, in the context of "restoration," what CERP aims and has the capacity to do in the Northern Estuaries includes creating or maintaining critical hydrologic characteristics conducive to supporting the health and diversity of the existing estuarine ecosystems. For this Performance Measure, reduction in incidences of flows that would result in undesirable salinity conditions is addressed; other PMs are necessary to address other characteristics of a healthy environment (e.g., water quality; see Appendix C). 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; USACE and SFWMD 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 Roosevelt Bridge for the SLE; salinities <10 in the upper CRE). 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 USACE and SFWMD [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 (USACE and SFWMD 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*]). The ecosystem services provided by oysters are extensive, and include top-down control of phytoplankton, filtration, nutrient cycling, benthic-pelagic coupling, refugia from predation, provision of habitat for other sessile as well as mobile species across different life history stages, and nesting habitat (Boudreaux et al. 2006; Cerco and Noel 2007; Coen et al. 2007; Buzzelli et al. 2013c). SAV are of vital importance for providing habitat and nursery grounds for a plethora of fish, invertebrates, and vertebrates including juvenile sea turtles and birds; the formation of plan and detrital-based food chains; nutrient cycling; and sediment stabilization (Klug 1980; Dawes et al. 1995; Torquemada et al. 2005; Chesnes et al. 2011). Key hypotheses supporting the selection of these species as ecological indicators are outlined in the RECOVER 2009 Monitoring and Assessment Plan (MAP) (RECOVER 2009). Appendix C outlines needs for future work, including the expansion of indicator species to detect changes across the estuarine salinity gradient, and modeling tools.

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 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.

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).*

Species	2007 PM Targets	2020 PM Optimum	2020 PM Stress	2020 PM 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 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, 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 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 alternative contributions toward restoration targets and 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. 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).

It was imperative to select an Optimum Flow Envelope for each estuary to benefit all indicator species to the greatest extent possible. Optimum Flow Envelopes for the SLE and CRE 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 (Table 2). For example, extreme high flows in the CRE could produce damaging salinities in the lower estuary for oysters, but tape grass prefers freshwater to low-salinity conditions.

***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 the 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 (ma) average Inflows to the SLE	The distribution of 14-day ma 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 ma Inflows to the CRE	The distribution of 14-day ma 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	More periods in the Optimum Flows is better; fewer periods in the low flows, or Stress and Damaging Flows is better. species.

Hydrologic Criteria	Description of RSM-BN Outputs (2100–2600 cfs) and Damaging Flow Envelope (>2600 cfs)	Targets
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 ma "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 ma flows over the POR that fall within the Optimum, Stress, and Damaging Flows for each estuary will represent the resulting flows observed with CERP project implementation. RSM-BN simulation results are run through "post-processing tools" (Appendix B) and outputs are represented by bar graphs of total counts (counts equaling the number of 14-day ma events out of an approximate 1,330 14-day periods over 51 years) within the Optimum Flow Envelope, low flows (below the Optimum Flow Envelope), Stress Flows, and Damaging Flows; and counts of consecutive 14-day ma events in the low flow, Stress Flows, and Damaging Flows.

More periods in the Optimum Flows is better, and fewer periods in the low flows or Stress and Damaging Flows is better. Ideally, project alternative simulations over the POR would yield no more than two (2) consecutive 14-day ma flow periods in the Stress Flow Envelope (three or more consecutive events would reflect >1 month of stressful salinities), and no more than one (1) consecutive 14-day ma flow periods in the Damaging Flow Envelope (two consecutive events would reflect ~1 month of damaging salinities) in either the SLE or CRE. These consecutive event targets are based on a precautionary approach in lieu of more sophisticated ecological modeling and insights from RECOVER monitoring. For example, mass mortality of oysters in the SLE in 2008 and 2017 were exposed to damaging salinities <5 for 20–25 days prior to the die-off; other mass die-offs in 2005, 2013, and 2016 were exposed to even longer durations of damaging salinities <5 or <1. Antecedent conditions relating to recent exposure to low salinities and high temperatures may be confounding factors, but again, more sophisticated, mechanistic models need to be developed to refine targets associated with magnitude, duration, and return frequency of high inflows (Appendix C).

Evaluation includes the distribution of flows using several condition simulations: (1) an Existing Base Condition (ECB) based on existing infrastructure or operations; (2) a Future Without Project (FWO) that includes a future scenario in which all currently authorized CERP projects

are completed, but excludes the current project being evaluated; and (3) future scenarios in which all currently authorized projects are completed, and include one of several different CERP project designs (i.e., Alternative I, Alternative II, Alternative III…) representing various infrastructure options or operational plans.

An example of how the flow distribution model outputs are generated and evaluated include post-processing results of several existing RSM-BN condition simulations using the revised Optimum Flow Envelopes (Figure 5). These simulations include two Lake Okeechobee operational scenarios pre- and post-LORS 2008, and two future scenarios with several authorized CERP projects (Table 4).

***Table 4**. Condition simulations (period of record 1965–2005) available from the Regional Simulations Model-Basins (RSM-BN) through which expected performance of CERP using the revised Salinity Envelope PM.*

Condition Simulation (POR 1965–2005)	Simulation Description and Model Assumptions
ECB-WSE	Existing Conditions Base with Water Supply/Environment (WSE), the previous Lake Okeechobee Regulations schedule before LORS 2008, which had been in effect since 2000.
ECB-LORS2008	Existing Conditions Base with the current Lake Okeechobee Regulations schedule (LORS 2008). The 2008 LORS schedule objective is to manage lower lake elevations (compared to WSE) to reduce risk to the Herbert Hoover Dike and to lessen the likelihood of high damaging discharges to the Caloosahatchee River and St. Lucie Estuaries.
FWO-LORS2008	Future Conditions with the current Lake Okeechobee Regulations schedule called LORS2008. In general, the future projected conditions include, relative to existing conditions, additional representations of planned future project activities, including currently authorized State, Federal and Central Everglades Restoration Project (CERP) projects, e.g., Indian River Lagoon-South and C-43 Projects.
LOWRP+CEPP C240	Starts with FWO-LORS2008 simulation and adds the Lake Okeechobee Watershed project (LOWRP), an additional storage feature of approximately 46,000 acre-feet (ac-ft) north of Lake Okeechobee; and the EAA storage reservoir project (CEPP C240) which includes 240,000 ac-ft of storage south of the lake.

Evaluating the four condition simulations (Table 4) using the revised Salinity Envelope Performance Measure (RECOVER 2007) Optimum Flow Envelope for the SLE (150–1400 cfs), general trends depict improvement in the flow regime between existing condition simulations to future simulations with CERP project implementation (Figure 5). Both the number of mean monthly flow events below the salinity envelope (<350 cfs), and 14-day ma flow events above the salinity envelope (>2000 cfs) decrease over time, with some differences among the four condition simulations. Note that these results are based on monthly low flows and 14-da ma

flows above the Optimum Flow Envelopes; in future, these will include the full distribution of 14-day ma inflows as defined in Table 3. All evaluation metrics here are still being coded into RSM-BN by the Interagency Modeling Center for future simulation modeling.

At the low flow bounds tested, the number of monthly mean flow is <150 cfs from both basin runoff and Lake Okeechobee Regulatory Releases over the POR decrease by 100% (from 3 to 0 times); and notably, the contribution of Lake Okeechobee Regulatory Releases triggering excursions of 14-day ma flows >1400 cfs decreases by 89% from ECB-WSE and LOWRP+CEPP240 (Figure 5). The fluctuation of those flow events >1400 cfs triggered by basin runoff between existing base and future condition simulations further exemplifies the need to address localized inflows within the expanded, channelized watershed, not just those from Lake Okeechobee.

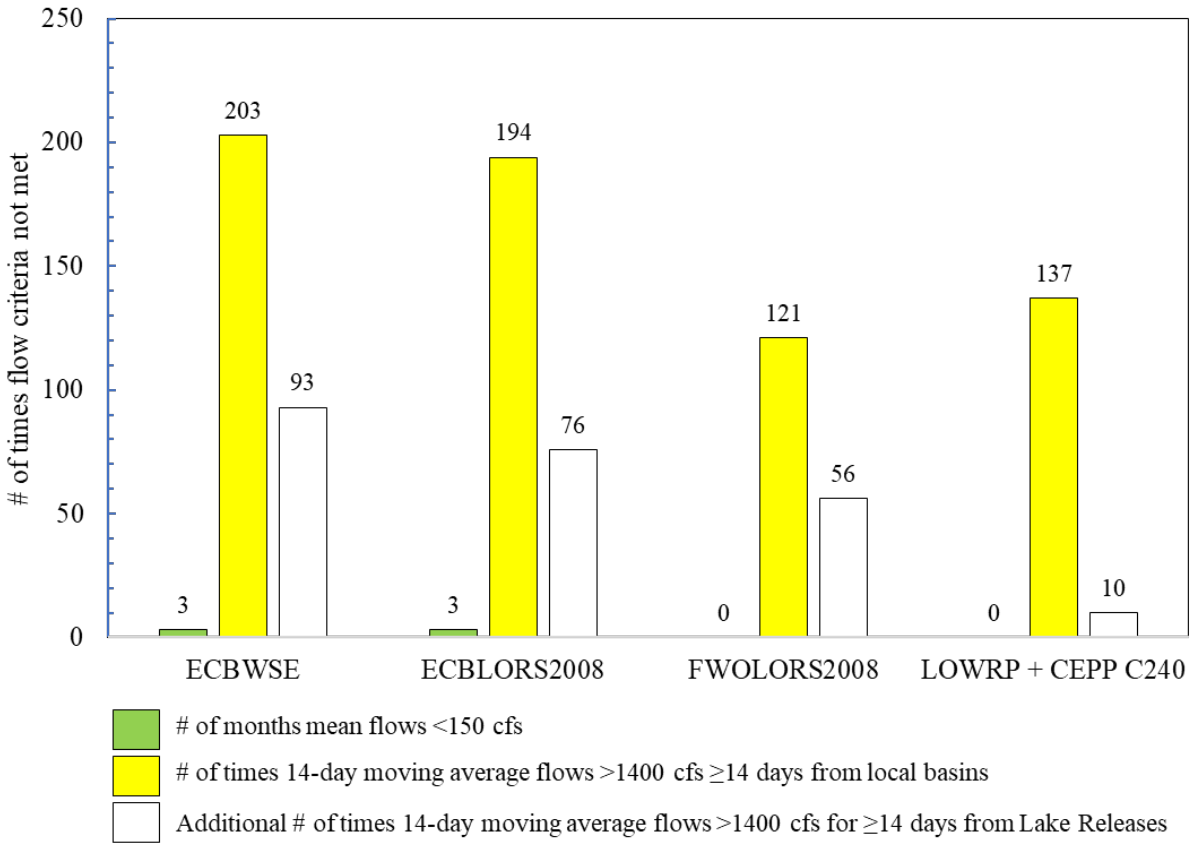

***Figure 5**. Number of times the 14-day moving average or monthly flows to the SLE fell below the Optimum Flow Envelope of 150–1400 cfs between the four condition simulations, over the period of record (1965–2005).*

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 additional 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 ma 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.

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).

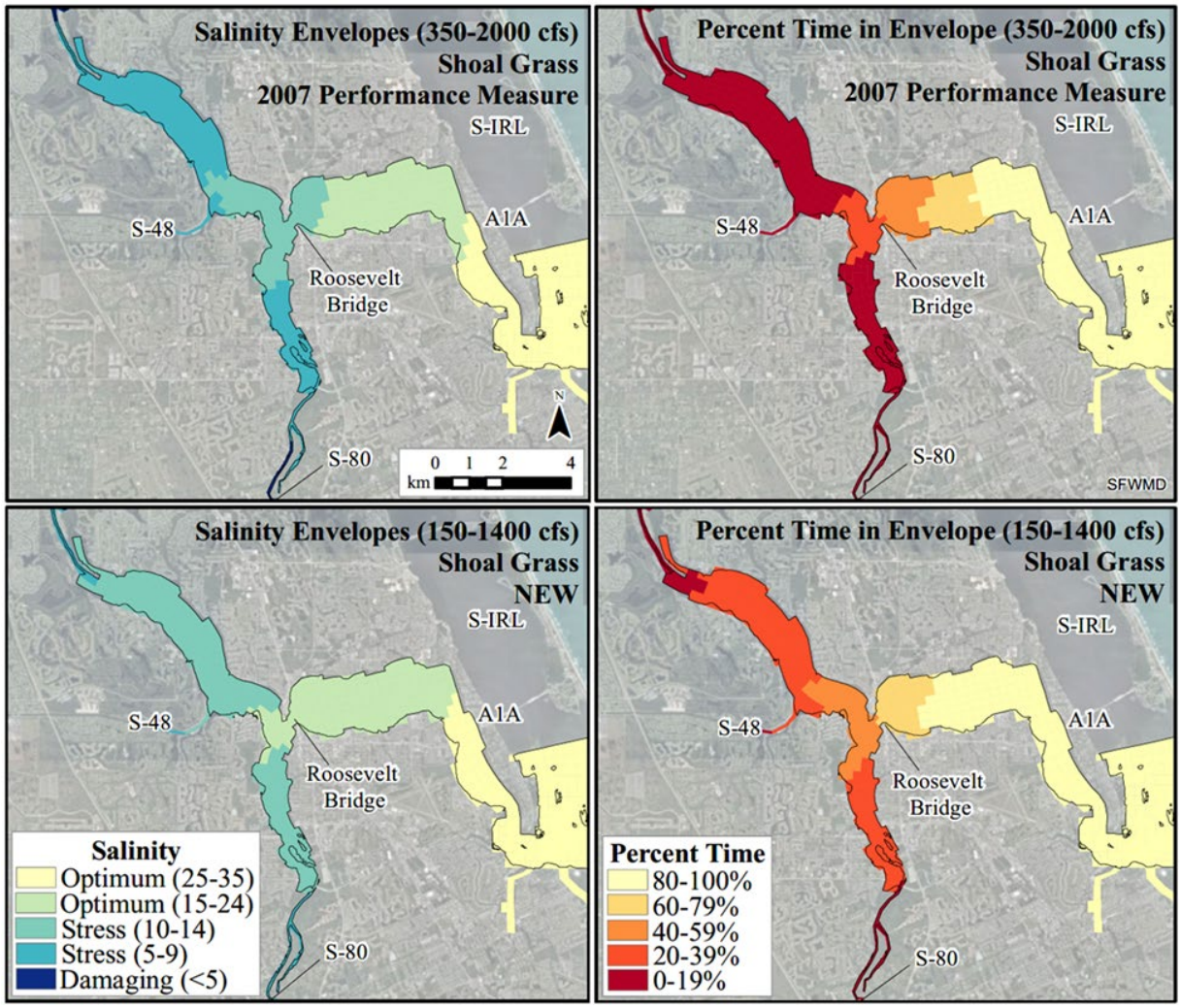

***Figure 6**. Mean salinity and percent time within Optimum Salinity Envelope for shoal grass (salinities 15–45) in the SLE modeled on target flows from the 2007 PM (350–2000 cfs) and the new, revised PM (150–1400 cfs). With the new, revised flow target, salinity conditions improve to optimum throughout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

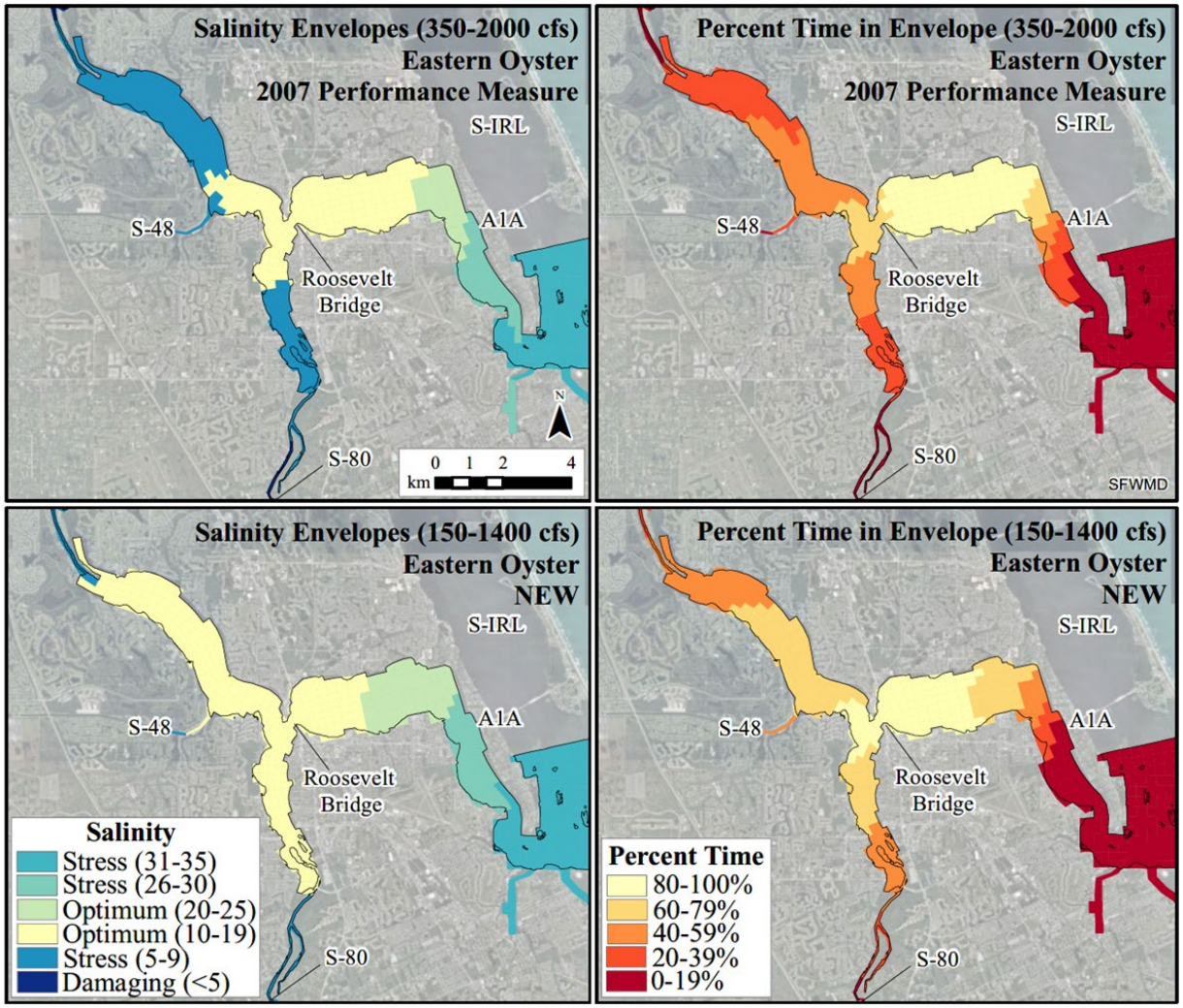

***Figure** 7. Mean salinity and percent time within Optimum Salinity Envelope for Eastern oyster (salinities 10–25) in the SLE modeled on target flows from the 2007 PM (350–2000 cfs) and the new, revised PM (150–1400 cfs). With the revised flow target, salinity conditions improve to optimum throughout 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

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.

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).

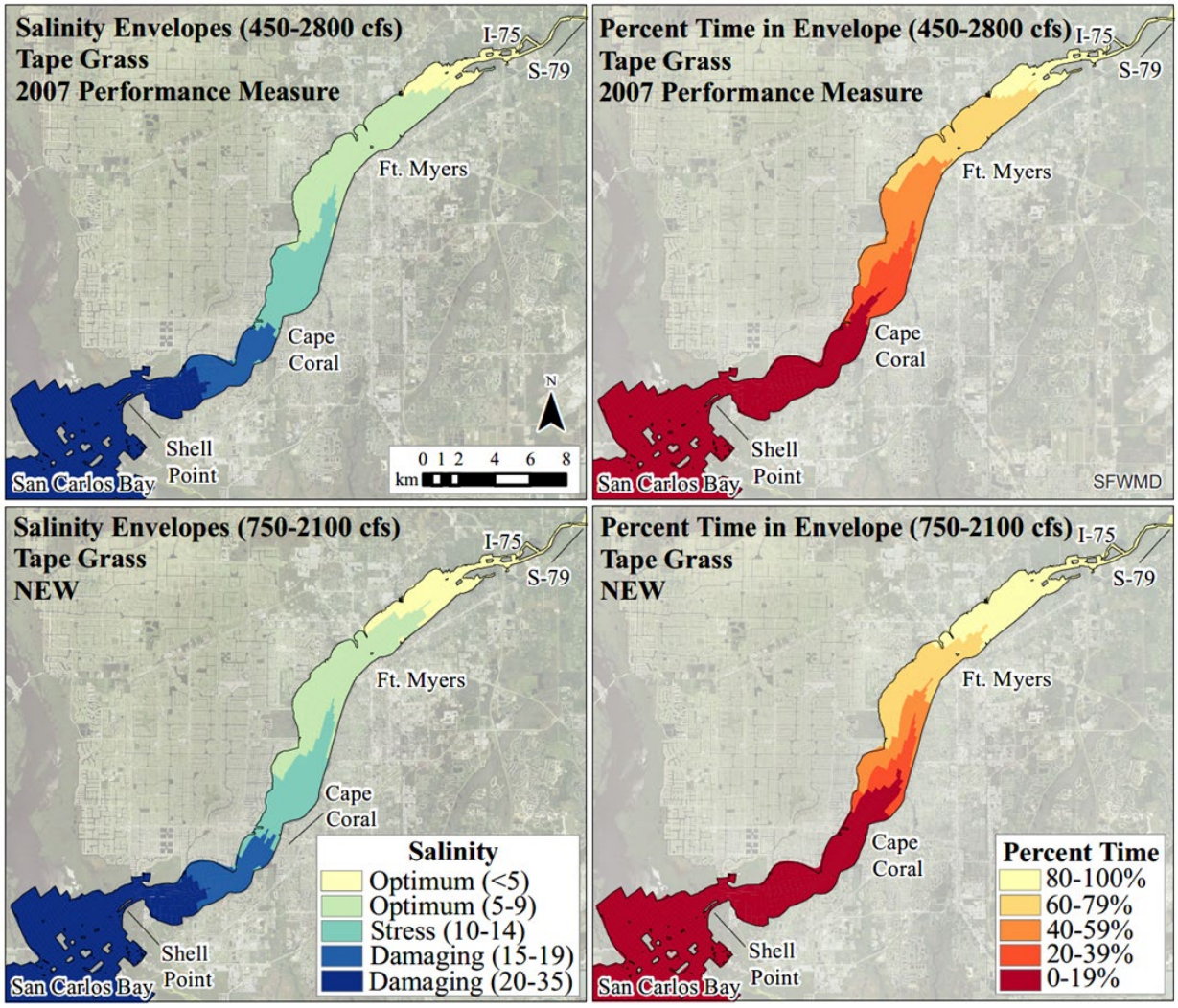

***Figure 8**. Mean salinity and percent time within Optimum Salinity Envelope for tape grass (salinities <10) in the Caloosahatchee River Estuary modeled on target flows from the 2007 PM (450–2800 cfs) and the new, revised PM (750–2100 cfs). With the revised flow target, salinity in the range of 0–5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

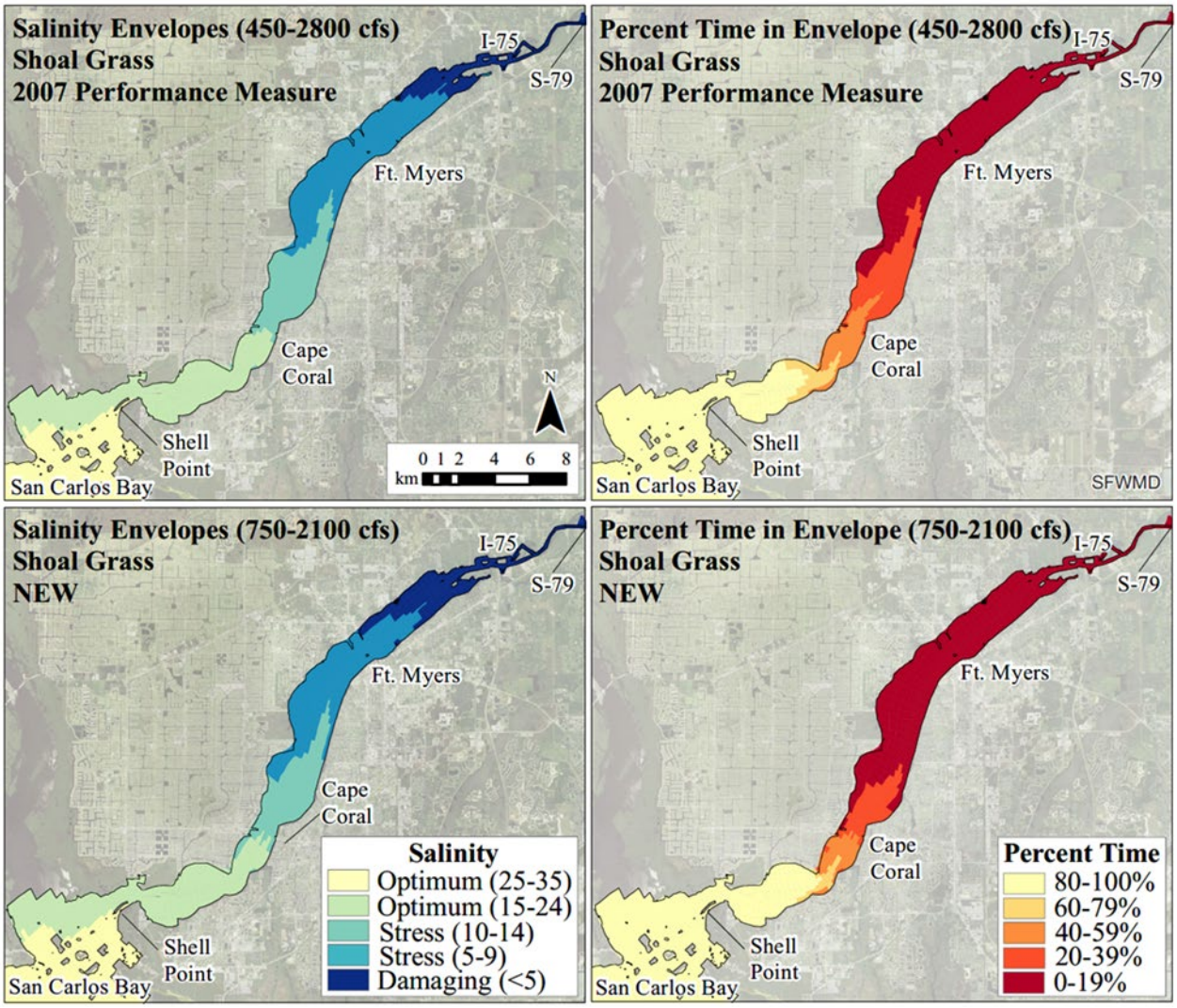

***Figure 9**. Mean salinity and percent time within Optimum Salinity Envelope for shoal grass (salinities 15–45) in the Caloosahatchee River Estuary modeled on target flows from the 2007 PM (450–2800 cfs) and the new, revised PM (750–2100 cfs). With the revised flow target, percent time within Optimum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

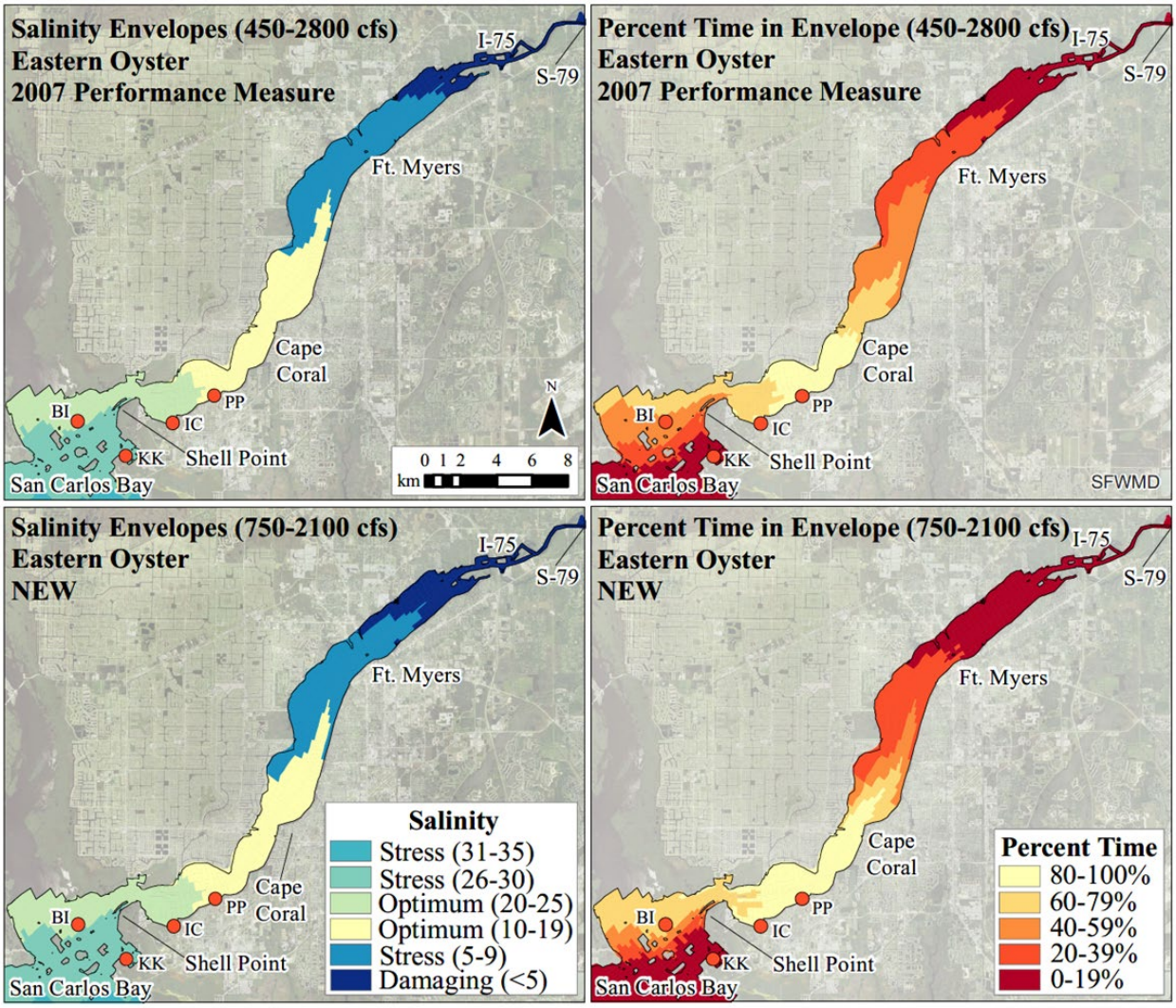

Figure 10. *Mean salinity and percent time within Optimum Salinity Envelope for Eastern oyster (salinities 10–25) in the Caloosahatchee River Estuary modeled on target flows from the 2007 PM (450–2800 cfs) and the new, revised PM (750–2100 cfs). Red circles indicate RECOVER oyster monitoring sites from 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 exercise using the CH3D hydrodynamic model was conducted to select Stress and Damaging Flow Envelopes, whereby iterative flow categories were modeled greater than the Optimum Flow Envelope for the SLE and CRE. Stress Flows and Damaging Flows were differentiated based on resulting salinity maps where salinities were within the Stress Salinity Envelope and Damaging Salinity Envelope (Table 1), respectively, in different reaches of the estuary. A precautionary approach was used based on 1) extent of the "stress" or "damaging zone" generated from each alternative flow envelope modeled; and 2) evaluating when a stress or damaging salinity occurred in areas where current populations of indicator species are supported, areas of transition on the upstream or downstream extents of current populations exist or are desired, or where ecological impacts can be detected based on the current RECOVER monitoring/sampling.

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, varying degrees 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]). 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.

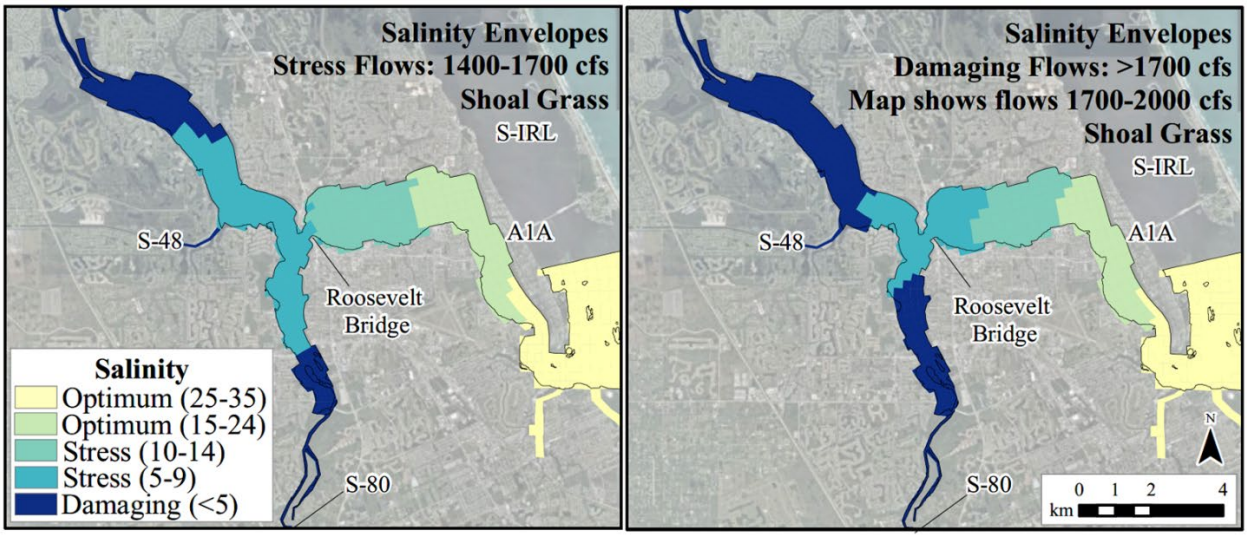

Figure 11. *Mean salinity ranges in the SLE for shoal grass (Optimum Salinity Envelope 15–45) resulting from Stress Flows 1400–1700 cfs (left) and Damaging Flows >1700 (right; depicts salinities resulting from flow 1700–2000 cfs). Salinities fall into the Stress Salinity Envelope for shoal grass (5–14) 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.*

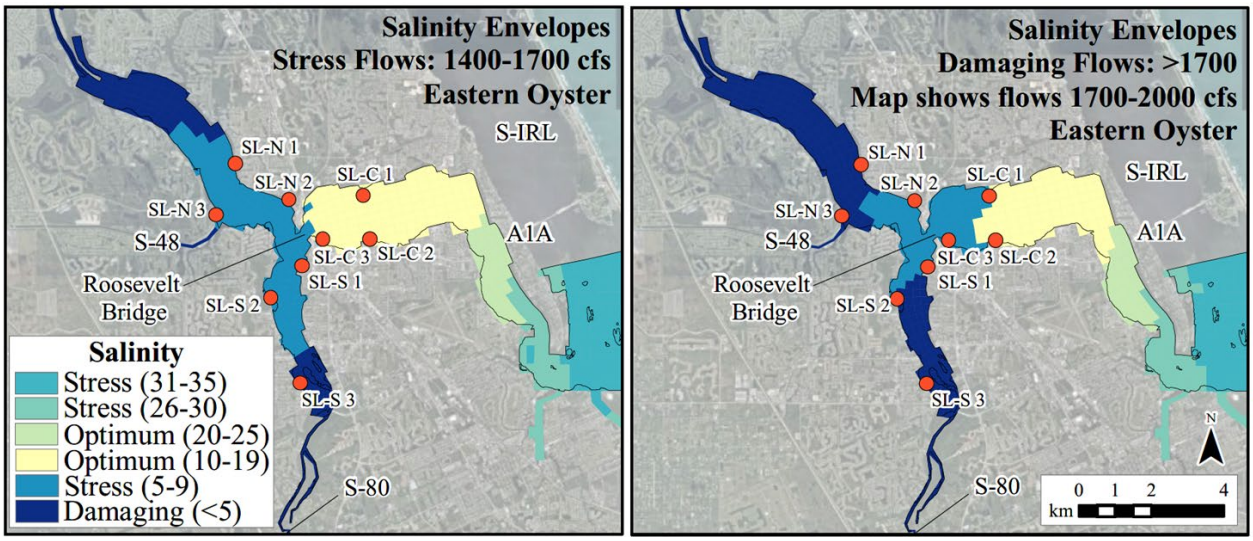

Figure 12. *Mean salinity ranges in the SLE for Eastern oyster (Optimum Salinity Envelope 10–25) resulting from Stress Flows 1400–1700 cfs (left) and Damaging Flows >1700 (right; depicts salinities resulting from flow 1700–2000 cfs). Red circles indicate RECOVER oyster monitoring sites: St. Lucie North 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.

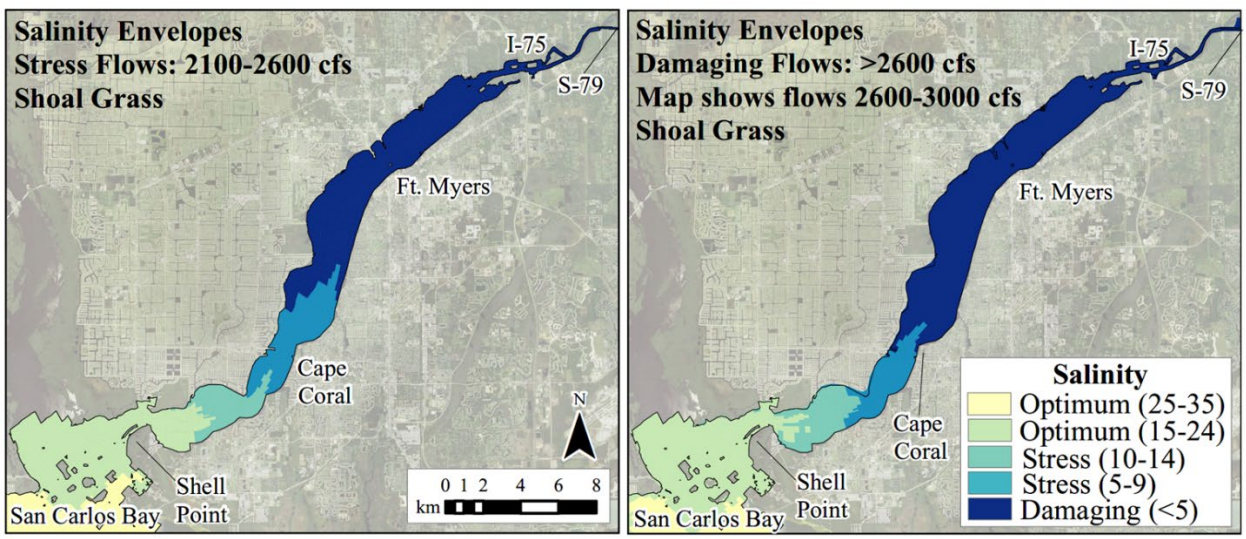

***Figure 13**. Mean salinity ranges in the CRE for shoal grass (Optimum Salinity Envelope 15–45) resulting from Stress Flows 2100–2600 cfs (left) and Damaging Flows >2600 (right; depicts salinities resulting from flow 2600–3000 cfs). Salinities fall into the Stress Salinity Envelope for shoal grass (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.*

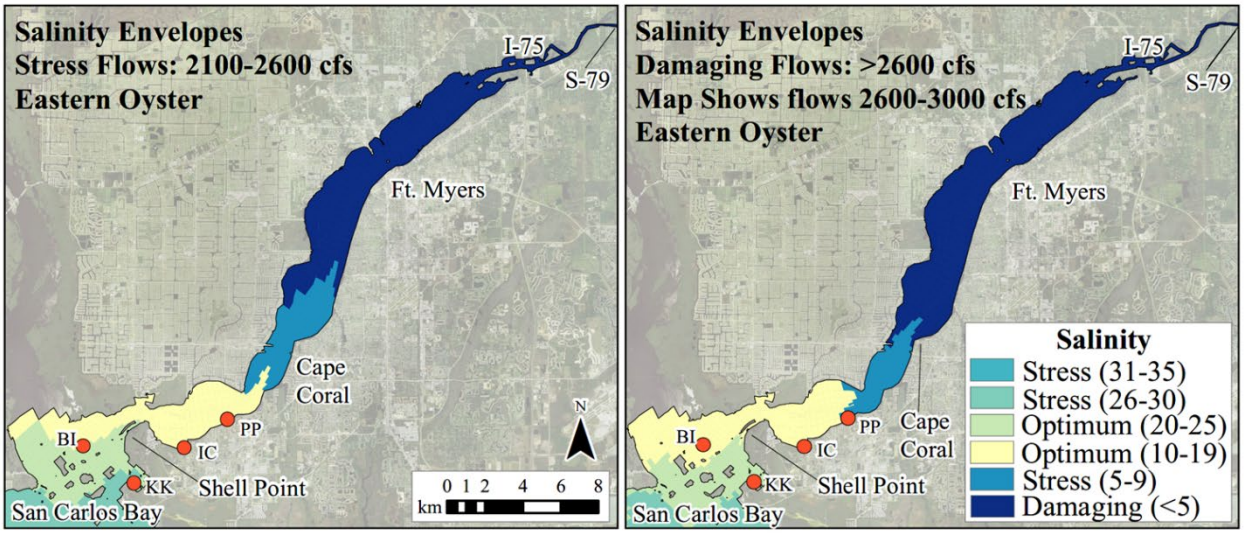

***Figure 14**. Mean salinity ranges in the CRE for Eastern oyster (Optimum Salinity Envelope 10–25) resulting from Stress Flows 1400–1700 cfs (left) and Damaging Flows >1700 (right; depicts salinities resulting from flow 1700–2000 cfs). Red circles indicate RECOVER oyster monitoring sites from upstream 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

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 51-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

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 below and SFWMD (2020b).
- For the purpose of understanding the difference between the Salinity Envelope PM flow targets for the CRE, and the revised CRE MFL: the Salinity Envelope PM provides biologically and ecologically-driven guidance to the CERP for establishing and maintaining salinity regimes to sustain healthy estuarine ecosystems, and are "restoration-based" targets; whereas the 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), and based on the significant harm threshold of "temporary loss of water resource functions, which result from a change in surface or ground water hydrology that takes more than two (2) years to recover (Subsection 40E-8.021[31]), F.A.C.)." Additionally, while this PM uses three (3) ecological indicator species (based on the EPA's VEC approach described in Section 2.1) to identify flow-salinity relationships and expected organismal and habitat response for restoration purposes, the MFL included analysis and modeling using data from 11 different indicator species to address the thresholds described above (SFWMD 2020b). To differentiate restoration and recovery, in this PM, restoration is referred to in the context of “renewing degraded, damaged, or destroyed ecosystems and habitats in the environment through human actions and active intervention”; whereas the Recovery Strategy outlined in the MFL includes the "development of additional water supplies and other actions, consistent with the authority granted by Chapter 40E-8, FAC to: 1) Achieve recovery to the established minimum flow or minimum water level as soon as practicable..."
- Additional modeling is needed to determine impacts of SLE Damaging Flows to the S-IRL and the Atlantic nearshore environment, and CRE Damaging Flows to San Carlos Bay and the Gulf of Mexico. These may be included as part of the Lake Okeechobee System Operating Manual (LOSOM) update. Where applicable, an addendum to this Salinity Envelope PM will be made to reflect the results of this additional modeling.
- 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 (LWL) was no longer included in the the RECOVER Northern Estuaries monitoring program; there are no CERP projects currently scheduled for planning or implementation expected to affect this estuary in the foreseeable future. For this PM update, RECOVER prioritized its resources to evaluate and assess the systems impacted by CERP projects identified in the IDS (i.e. SLE and CRE) but recognizes LWL is an estuary of importance to the greater southeast Florida region impacted by the C&SF Project, and therefore for regional water planning. An updated hydrodynamic model for the LWL needs to be developed to establish flow targets commensurate with those for the SLE and CRE; and the RSM-BN model zone is currently being expanded to include the North Palm Beach area, in which inflows to LWL can be captured in future simulation modeling.

7 NORTHERN ESTUARIES WORKING GROUP & RECOVER REVIEW PROCESS

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

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Michael C. Brown, SFWMD
Robert Chamberlain, SJRWMD
Zhiqiang Chen, SFWMD
Peter Doering, SFWMD retired
Susan Gray, SFWMD retired
Harold Hennessey-Correa, SFWMD
Lori Morris, St. Johns River Water Management District (SJRWMD)
Melanie Parker, FFWCC FWRI
Patrick Pitts, USFWS retired
Barbara Welch, SFWMD
Walter Wilcox, SFWMD

And finally:

Interested members of the public who took time out of their day to provide comment on the draft Documentation Sheet during a global pandemic – thank you!

The formal RECOVER review process for this Salinity Envelope PM update included several reviews and comment periods (with revisions between review dates), and informational webinars (Table 5).

***Table 5**. Dates of reviews and comment periods and informational meetings during the formal RECOVER review process for the Salinity Envelope PM Documentation Sheet.*

RECOVER Review Period or Informational Meeting	Dates
Northern Estuaries Regional Team Review	2/1–2/29/2020
Informational Webinar for Northern Estuaries Regional Team	2/19/2020
Informational Webinar to RECOVER Regional Coordinators, Executive Committee (REC) and RECOVER Leadership Group (RLG)	3/19/2020
REC Review	4/1–4/15/2020
RECOVER-wide and Public Comment Review Period*	4/28–5/28/2020
Informational Webinar for RECOVER and Public	4/29/2020
Informational Webinar for RECOVER and Public	5/5/2020
2nd REC Review and RLG Review	6/17–6/28/2020
Documentation Sheet Finalized	7/X/2020

*Review period extended to 30 days, instead of the typical 10-day reviews for PM updates

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APPENDIX A: The CH3D Hydrodynamic Salinity Model for the St. Lucie and Caloosahatchee Estuaries

1 INTRODUCTION

The curvilinear hydrodynamic three-dimensional model (CH3D; Sheng 1986) uses a horizontal boundary-fitted curvilinear grid and vertical sigma grid system capable of simulating complicated hydrodynamic processes including wind and 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 and 1987; Sheng and Villaret 1989). The non-orthogonal nature of the model enables it to represent the complex geometry of an estuary such as the St. Lucie Estuary (SLE) and Caloosahatchee River Estuary (CRE). The model is driven by external forcing prescribed at the boundaries, including tidal forcing at the ocean boundary, freshwater inflow from controlled structures and runoff from the watershed, and meteorological forcing including wind and rainfall/evaporation. Major assumptions for the CH3D hydrodynamic model are the hydrostatic approximation (shallow water equation), Reynold stress turbulence closure, and log law boundary layer approximations (Sheng 1986).

2 THE ST. LUCIE ESTUARY CH3D MODEL

The model domain covers the North Fork, North Fork Narrow, South Fork, the estuary proper down to the St. Lucie Inlet, and part of the southern Indian River Lagoon up to Vero Beach, and includes some offshore areas outside the St. Lucie Inlet (Figure 1). The horizontal grid has approximately 1200 cells with higher resolutions for the navigation channel, and coarser grids in the offshore and out of the inlet. The grid size ranges from 30–100 m. Vertically, four evenly spaced sigma-layers enable simulation of vertical stratification within the estuary. The CH3D model was converted from the EFDC (Environmental Fluid Dynamics Code) and validated with data from two years (1999 and 2000). It was later extended and further validated with six more years (2001–2006) of salinity data observed at three continuous monitoring stations (A1A, US-1, and HR1 [Figure 1]) together with monthly grab samples from additional monitoring stations in the estuary (Sun 2009). The model has been applied to the St. Lucie North Fork Water Reservation Study (Sun 2009). It was also coupled with a stand-alone water quality model to study nutrient, phytoplankton and dissolved oxygen dynamics in the estuary (Sun et al. 2018).

For this Salinity Envelope Performance Measure (PM) update, the model was used to simulate salinity for the 51- year period from January 1, 1965 to December 31, 2015 using historical daily flow data at S80, S48, S49, Gordy Road Structure and modeled tidal basin runoff, hourly tides at the offshore boundaries and meteorological forcing (hourly wind and daily rainfall/evaporation) at the water surface. The major output application for this Salinity Performance Measure was 14-day averaged salinity at every grid cell, i.e., a simple average over every 14-day period, not a moving average. However, daily and even finer temporal output options are also available since the model uses a 60 second time step.

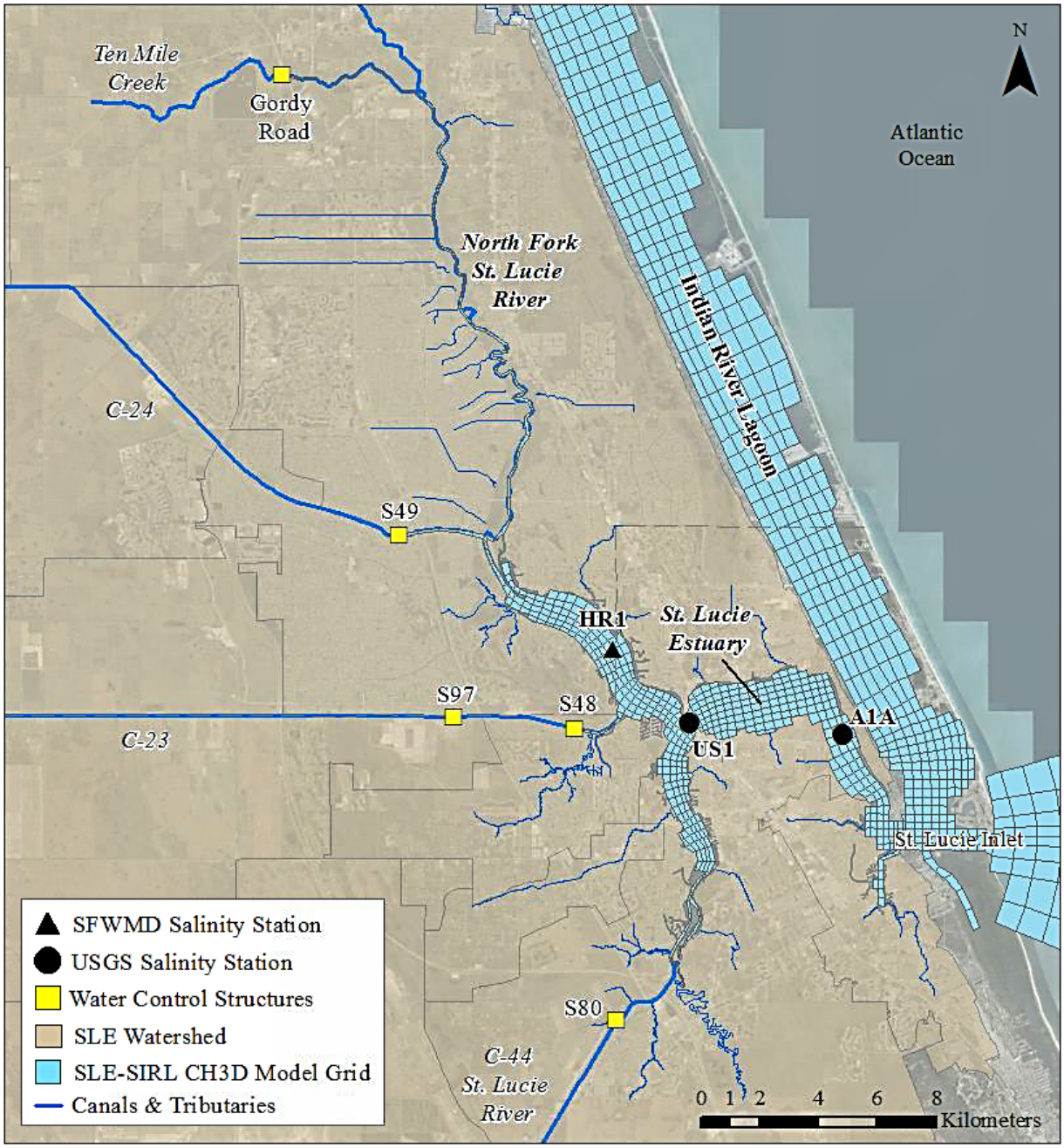

***Figure 1**. The CH3D model grid for the St. Lucie Estuary (SLE) and continuous data monitoring stations used for model calibration.*

3 THE CALOOSAHATCHEE RIVER ESTUARY CH3D MODEL

The model domain covers the CRE, Charlotte Harbor, Pine Island Sound, San Carlos Bay, Estero Bay, and all the major tributaries (Figure 2). 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 m 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 50–100 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), now the Coastal and Heartland Estuary Partnership (CHNEP). The SFWMD extended the model calibration to the CRE portion using a 16-month time series for the 2003 Minimum Flows and Minimum Water Levels (MFL) update (Qiu 2002). In 2005, the Caloosahatchee portions of the model were calibrated with three years of measured data (2001–2004) from five stations in the Caloosahatchee Estuary (Qiu et al. 2006). Recently, the calibration of the model was further refined using salinity and tide data collected at seven monitoring stations (S-79, BR31, ValI75, Ft. Myers/Marker 52, Cape Coral, Shell, Point, and Sanibel [Figure 2]) in the CRE (Sun et al. 2016). The model was one of the major tools used for the most recent CRE MFL update (SFWMD 2020).

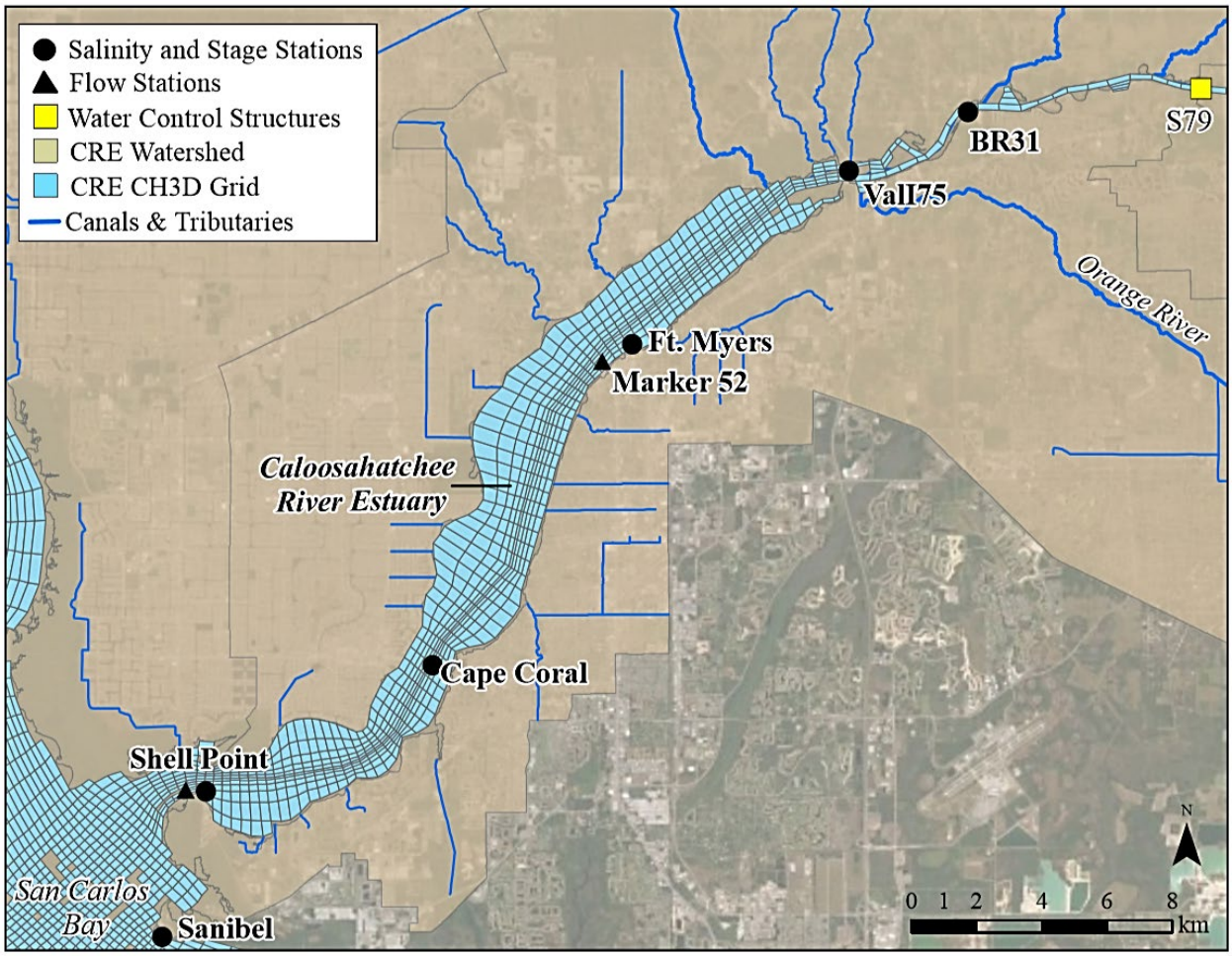

***Figure 2**. The CH3D model grid for the Caloosahatchee River Estuary (CRE) and continuous data monitoring stations used for model calibration.*

For this Salinity Envelope PM update, the model was used to simulate salinity for the 51- year period from January 1, 1965 to December 31, 2015 using historical daily flow data at S-79 and modeled tidal basin runoff (SFWMD 2020; Appendix D), hourly tides at the offshore boundaries and meteorological forcing (hourly wind and daily rainfall/evaporation) at the water surface. The

major output for the Salinity Performance Measure application was 14-day averaged salinity at every grid cell. However, daily and finer temporal outputs are also available since the model uses a 90 second time step.

4 MODEL UNCERTAINTY FOR SALINITY PRDICTION

The CH3D hydrodynamic model is a well-tested hydrodynamic model with appropriate assumptions and solid numerical algorithm with sufficient accuracy. The major uncertainty of the hydrodynamic model can usually be attributed to inaccuracy in its boundary conditions. For salinity the most important boundary conditions are freshwater discharges. The model considered all the freshwater sources. Most sources are gauged through structures. The ungauged flows are tidal basin runoff and include groundwater contributions, which are estimated through the WaSh (WaterShed) hydrological model that was calibrated with limited tributary flow data (see Wan et al., 2003 for the SLE; SFWMD, 2020 Appendix D for the CRE). Discharge from Lake Okeechobee is via C-44 then through S-80 to the SLE and through S-79 via C-43 to the CRE. However, S-80/S-79 flows also have the contribution from the corresponding C44/C43 basins.

To examine model performance in salinity, Figure 3 and 4 are comparisons between modeled and observed daily salinity at US-1 Roosevelt Bridge for the SLE and Ft. Myers for the CRE respectively. Table 1 are R^2 values between modeled and observed daily salinities, a commonly used model performance metric, at three continuous monitoring stations in the SLE and seven monitoring stations in the CRE. The comparisons and statistics are for the period from 2000 to 2015 for both estuaries. The results demonstrate very solid model performance for both estuaries with R^2 values greater than 0.85 for every station except Sanibel in the CRE. The outlier at Sanibel is likely because it's a station outside the main estuary and is influence more by offshore boundary and by factors other than freshwater discharges.

Detailed calibration/verification for the CH3D model can be found in Sun (2009) and Sun et al. (2016).

Table 1. *R^2 values between modeled and observed daily salinities at three SLE and seven CRE monitoring stations for the period from 2000–2015.*

SLE			**CRE**		
Station	Surface	Bottom	Station	Surface	Bottom
HR1	0.88	0.85	S-79	0.88	0.88
US-1	0.90	0.84	BR31	0.91	0.87
A1A	0.89	0.80	VALI-75	0.89	0.89
			Ft. Myers	0.95	0.94
			Cape Coral	0.96	0.94
			Shell Point	0.89	0.84
			Sanibel	0.69	0.70

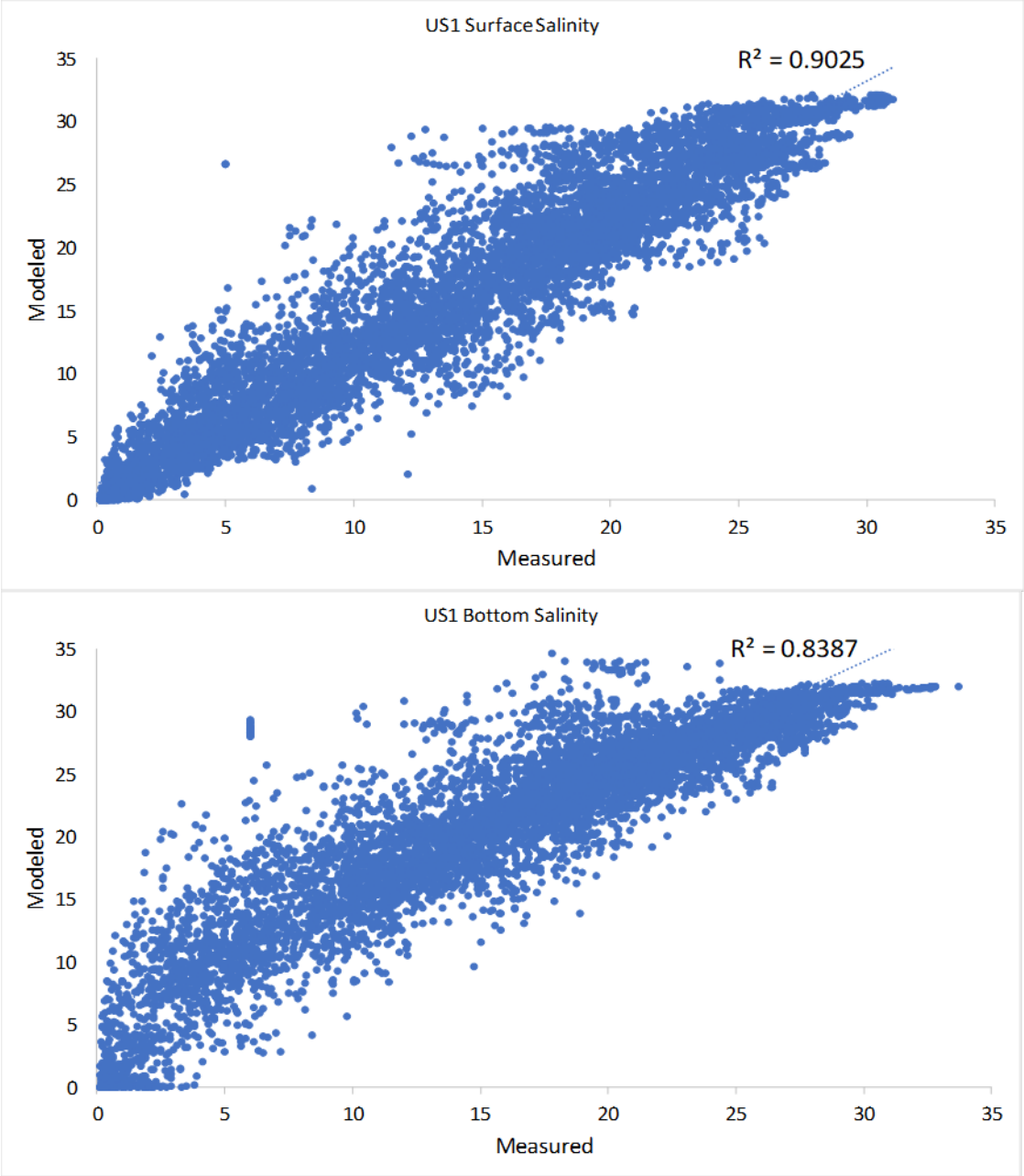

Figure 3. *Modeled daily surface (top) and bottom (bottom) water salinity vs. measured at US-1 Roosevelt Bridge in the SLE for the 15-year period from 2000 to 2015.*

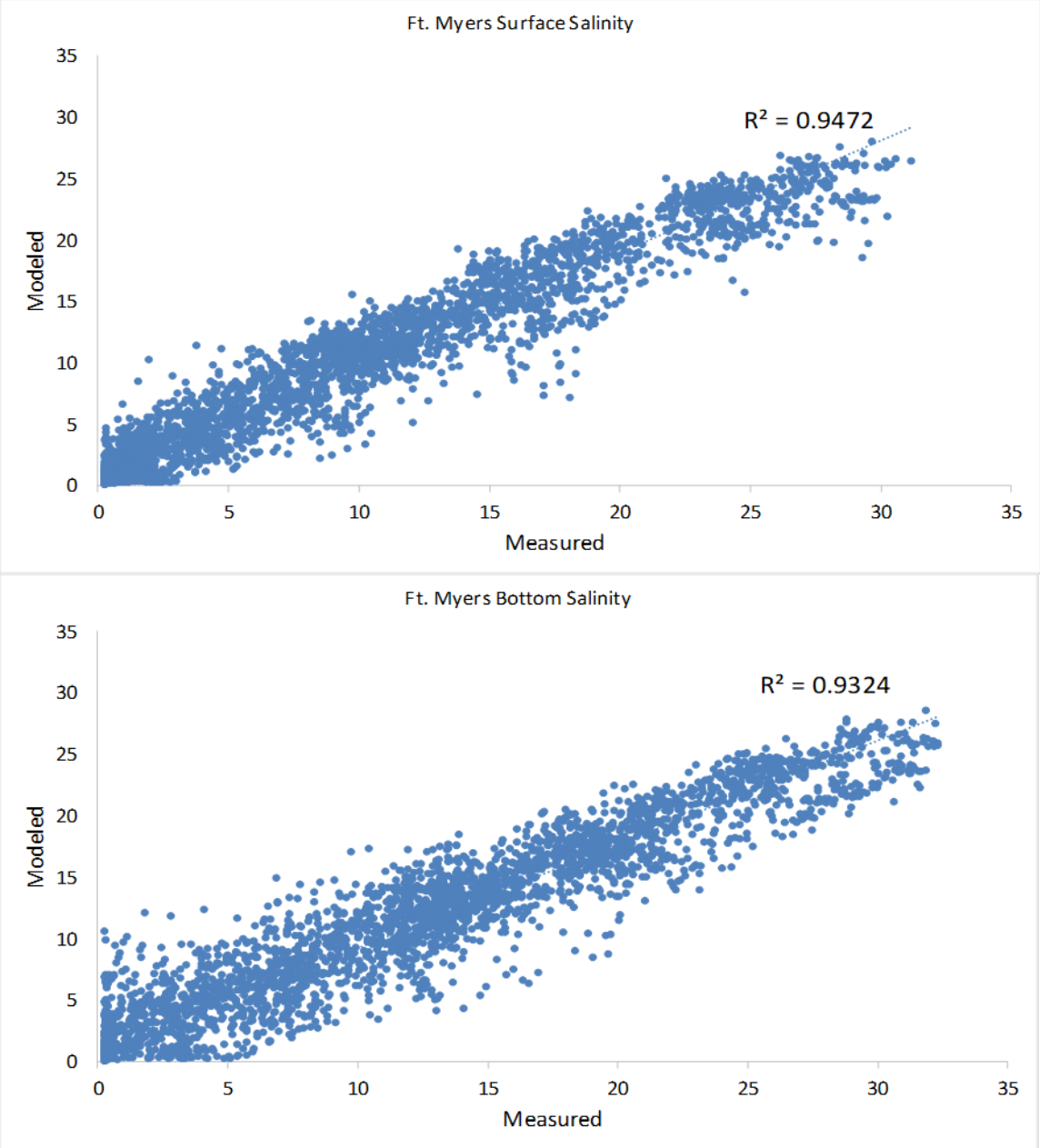

Figure 4. *Modeled daily surface (top) and bottom (bottom) water salinity vs. measured at Ft. Myers in the CRE for the 15-year period from 2000 to 2015.*

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APPENDIX B: A Conceptual Habitat Area-Based Approach, and Performance Measure Post-Processing Tools for Evaluation of Flow Envelope Alternatives

1 INTRODUCTION

Using the updated Salinity Envelopes (Table 1 in the main Northern Estuaries Salinity Envelope Documentation Sheet ["Documentation Sheet"]), the following describes how the corresponding Flow Envelopes were derived for the St. Lucie Estuary (SLE) and the Caloosahatchee River Estuary (CRE). Mathematically, this was an inverse approach to answer the question as to what freshwater flows achieve the desirable salinity conditions in an estuary, vs. the question of what the salinities would be given known flow conditions. The former can now be reliably answered by a hydrodynamic-salinity model, while the latter has no empirical answer due to the 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. For example, to reduce the salinity to a specific condition at a given location in the estuary, higher flows are generally required in the dry season than in the wet season. In addition, there are other contributing factors such as tides at the offshore boundary and physical wind forces at the water surface which increases complexity of this relationship.

In the development of the 2007 Performance Measures for the SLE and CRE (RECOVER 2007), hydrological modeling of natural system flows and steady state hydrodynamic modeling of salinities were used to help determine appropriate flow envelopes for the chosen indicators (SFWMD 2004; Chamberlin and Doering 2001). There are some limitations to these approaches: hydrological conditions have significantly (and irreversibly) changed from natural system flow conditions and estuaries are very dynamic. A steady state hydrodynamic/salinity model is unable to capture the significant variation of salinity conditions in the estuary. The modeling approach employed for this Performance Measure update is described in the main Documentation Sheet (Evaluation Application, Section 3) and below.

Additionally, Performance Measure post-processing tools used during CERP Project Alternative Evaluation were employed to compare Optimum Flow Envelope alternatives.

2 CONCEPTUAL HABITAT AREA AND SENSITIVITY ANALYSES

2.1 Methodology

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. First, a well-calibrated and verified three-dimensional hydrodynamic-salinity model, CH3D (Curvilinear Hydrodynamic 3-Dimensional; Sheng 1986; 1987) was applied to simulate long-term (1965–2015) salinity using historical daily flow data from upstream gauge locations, tides at the offshore boundaries, and meteorological influences (wind, rainfall, evaporation) at the water surface. A brief description of the CH3D models for the SLE and CRE is given in Appendix A.

Second, a potential habitat area (PHA) was computed based on the updated Optimum Salinity Envelopes for the ecological indicators selected (Table 1, Documentation Sheet). Specifically, for each grid cell k in the model, if the salinity in the cell averaged over a 14-day period is within the Optimum Salinity Envelope, the area for the cell would be counted as potential habitat area (PHA) and the total area over the two-week period would be:

$$PHA(i) = \sum_k A_{k,i}$$

When S(k,i) is within an optimum range for an indicator, S is salinity averaged over a 14-day period, and i is the number of 14-day periods counted from January 1, 1965.

The third step, an average PHA for a given flow range (Q_{low} to Q_{high}) was computed:

$$APHA(Q_{low}, Q_{high}) = \frac{\sum_i PHA(i)}{T}$$

where Q_i is within the given flow range and Q_i is the flow averaged over the ith 14-day period, and T is the total number of 14-day periods in 51 years when the flow Q meets the given range.

For example, the 2007 PM flow target for the SLE is 350–2000 cfs (RECOVER 2007), thus T would be the total number of the two-week periods when the total inflow into the SLE was within the flow target, PHA(i) would be potential area where salinity falls within the Optimum Salinity Envelope for the selected indicator at the ith period when flow Q_i is within the 350–2000 cfs range, and the APHA would be the average potential habitat area for the selected indicator for the time whenever flow Q is within 350–2000 cfs. Note that the flow Q used for the SLE is the total flow into the estuary while for CRE, Q is the flow at S-79 to be consistent with the 2007 Salinity Envelope Performance Measure.

The lower and upper flow bounds were then incrementally adjusted and APHA for each adjustment was computed, resulting in a series of sensitivity curves (Figure 1–Figure 5). Note that in Figure 1–Figure 5, APHA was normalized to the APHA for the 2007 Salinity PM flow range for each estuary, therefore the result is a relative area with respect to the 2007 PM flow target performance. Further details are provided in descriptions for each estuary.

2.2 Results: Sensitivity Analysis and Selection of Optimum Flow Envelopes

2.2.1 St. Lucie Estuary

Figure 1 and Figure 2 are the computed relative APHA for shoal grass and oysters, respectively, where the x-axis is the high flow bound ranging 1000–2400 cfs in 200 cfs increments, and the y-axis represents the computed habitat area for each indicator relative to the 2007 PM for the SLE. Each curve represents one lower flow bound from 150–450 cfs in 100 cfs increments. The red dot is the APHA performance for the 2007 PM target (lower bound flow 350 cfs and upper bound flow 2000 cfs) and has a score of 1.0 on the y-axis. Within the plots, values greater than 1.0 would suggest better performance, i.e., a greater area within the Optimum Salinity Envelope for that indicator, relative to the 2007 PM. This implies a fundamental assumption: the computed

PHA was used as a surrogate based solely on salinity as potential habitat for each indicator in this estimation of predicting indicator performance. Ideally, the next step for calculating and predicting indicator performance (e.g., biomass and productivity) is to develop ecological models (Appendix C).

The sensitivity curves (Figure 1 and Figure 2) offered a number of Optimum Flow Envelope alternatives that took into account each ecological indicator's sensitivity (i.e., flows from the part of the curve >1.0 on the y-axis), from which a final selection was made to best balance benefits across all indicator species.

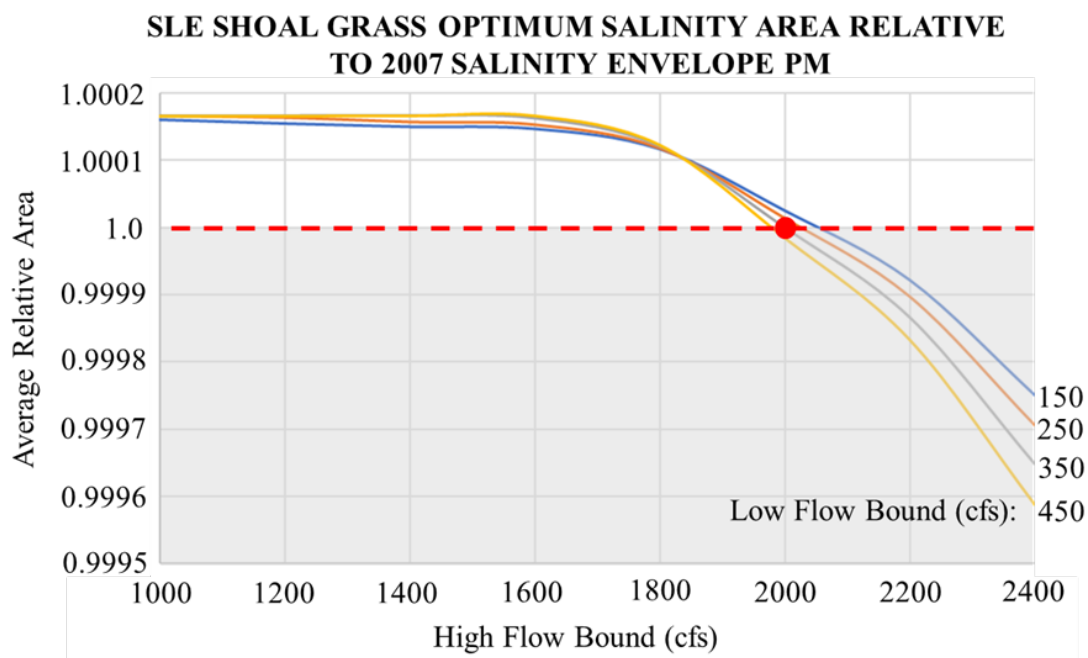

***Figure 1**. St. Lucie Estuary (SLE) shoal grass Optimum Salinity (salinities 15–45) area, i.e., Potential Habitat Area (PHA) based on 14-day average salinity, relative to the SLE 2007 Salinity PM Flow Envelope (red dot: 350–2000 cfs, a score of 1.0 on the y-axis). High flow bounds on the x-axis, low flow bounds represented by colored lines, labeled on the right of the plot.*

Selecting Optimum Flow Envelope alternatives for the SLE was straightforward in that shoal grass was not a sensitive indicator for the flow envelopes tested (Figure 1). There was little difference between the low flow bounds (150, 250, 350, and 450 cfs) until the high flow bound exceeded 1800 cfs, at which point the average relative area began to decrease, though only by hundredths of a percent. The spatial area bound for shoal grass was in the lower SLE and part of the southern Indian River Lagoon (IRL) in proximity to the St. Lucie Inlet, north to the A1A bridge in the southern IRL and therefore the lack of sensitivity is likely a factor of tidal influence on salinity.

For oysters, sensitivity was evident at combinations of higher low flow bounds, and higher high flow bounds (Figure 2). The greatest improvement in average relative PHA (21–23%

improvement) included lower low flow bounds and lower high flow bounds. High flow bounds starting at 1200 cfs and incrementally increasing by 200 cfs to 1600 cfs was selected for further evaluation, wherein it estimated that average relative PHA would increase by 5% from 1600 cfs to 1400 cfs, and another 5% from 1400 cfs to 1200 cfs, though the percentage increase minimal at lower flow bounds of 150 and 250 cfs.

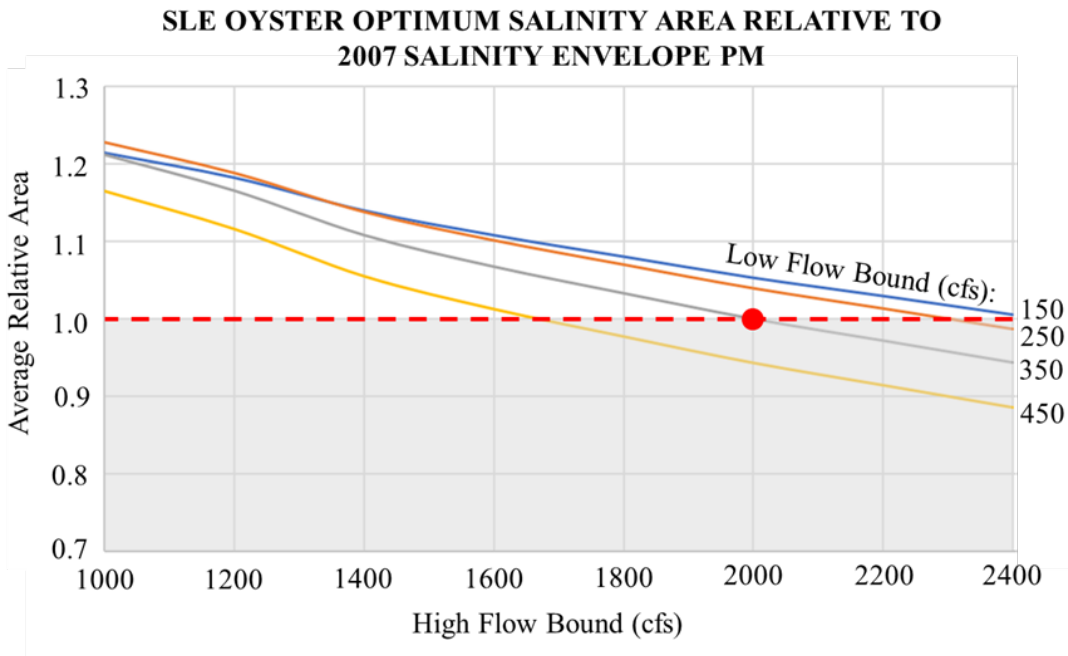

***Figure 2**. St. Lucie Estuary (SLE) Eastern oyster Optimum Salinity (salinities 10–25) area, i.e., Potential Habitat Area (PHA) based on 14-day average salinity, relative to the SLE 2007 Salinity Envelope PM flow envelope (red dot: 350–2000 cfs, a score of 1.0 on the y-axis). High flows are on the x-axis, low flows represented by the colored lines, labeled to the right of the plot. Flow Envelopes above the red dashed line/grayed area indicative of an improvement in PHA (based on Optimum Salinity) by 10, 20, and 30%.*

Interpretation of the Natural Systems Model (NSM) for the SLE watershed, which was developed during Indian River Lagoon-South Project planning process (IRL-South Project Implementation Report and Environmental Impact Statement; USACE and SFWMD 2004), provides some additional context for selecting the range of Flow Envelopes evaluated with support for the selected envelope that encapsulates a greater range of flows (e.g., >1000 cfs at the upper end). The NSM simulated that the flow-frequency distribution of flow categories <350 cfs and 350–680 cfs are an estimated 72.5% and predicted another 13% flow-frequency distribution in the 680–1340 cfs range (USACE and SFWMD 2004). Additional justification for a broader flow envelope includes uncertainty in the NSM defining the probability of low and high monthly flows to the estuary, and the importance of reducing shock to the both the oligohaline and mesohaline zones (USACE and SFWMD 2004). The selected Optimum Flow Envelope alternatives evaluated further using salinity maps (see main Documentation Sheet, Section 4) would allow for testing modeled salinity effects and therefore suitable flow regimes for the protection of the different reaches of the estuary. The SLE does not currently for this PM have an

oligohaline indicator, but this would be a valuable addition (e.g., tape grass in the upper North Fork) to track impacts to the oligohaline (riverine) zones (Appendix C).

2.2.2 Caloosahatchee River Estuary

Like the SLE, Figure 3–Figure 5 are the relative PHA for three indicators in the CRE: Eastern oyster, shoal grass, and tape grass respectively. The high flow bound range (x-axis) is 1800–3000 cfs in 200 cfs increments, and each curve represents one lower flow bound from 450–750 cfs in 100 cfs increments. The red dot is the value from the 2007 PM target (lower bound flow 450 cfs and upper bound flow 2800 cfs) and has a score of 1.0 on the y-axis (relative PHA based on salinity). Within the plots, values greater than 1.0 would suggest better performance, i.e., a greater area within the Optimum Salinity Envelope for that indicator, relative to the 2007 PM. The same fundamental assumption is true: the computed PHA was used as a surrogate based solely on salinity as potential habitat for each indicator in this estimation of predicting indicator performance.

Selecting Optimum Flow Envelope alternatives for the CRE had an additional challenge that required balancing the salinity optima of a freshwater/oligohaline SAV species (i.e., tape grass) in the upstream estuary, and mesohaline/marine SAV (i.e., shoal grass) and the Eastern oyster (meso/polyhaline) downstream. By comparing plots, estimations were made as to which alternatives could provide an estuarine salinity gradient most suitable for these three ecological indicator species.

Oysters were less sensitive than shoal grass at increased high flow bound volumes in excess of 2300 cfs, depending on the low flow bound. This is expected, as the low end of the optimum salinity range for oysters is salinity of 10, whereas shoal grass is salinity of 15. Average relative PHA for oysters improved by 3–14% across all flow envelopes tested with a minimum low flow bound of 550 cfs (Figure 3). Both oysters and shoal grass performed best at a high flow bound of approximately 2000 cfs. Average PHA for oysters decreased slightly at 1800 cfs, which indicates that continued decreases in the high flow bound <1800 cfs would cause a commensurate decrease in PHA due to increased salinity. Relative PHA for shoal grass continued to increase with < 2000 cfs, as expected due to its preference for higher salinities (Figure 4).

Tape grass sensitivity had the opposite trend, with higher relative average PHA with both higher low flow bounds and higher high flow bounds (Figure 5); this is expected for a freshwater/oligohaline SAV species. The flow envelopes indicative of increased relative PHA for tape grass are conversely less beneficial (or detrimental) to mesohaline and marine species downstream at high flow bounds greater than 2300 cfs (Figure 3 and Figure 4).

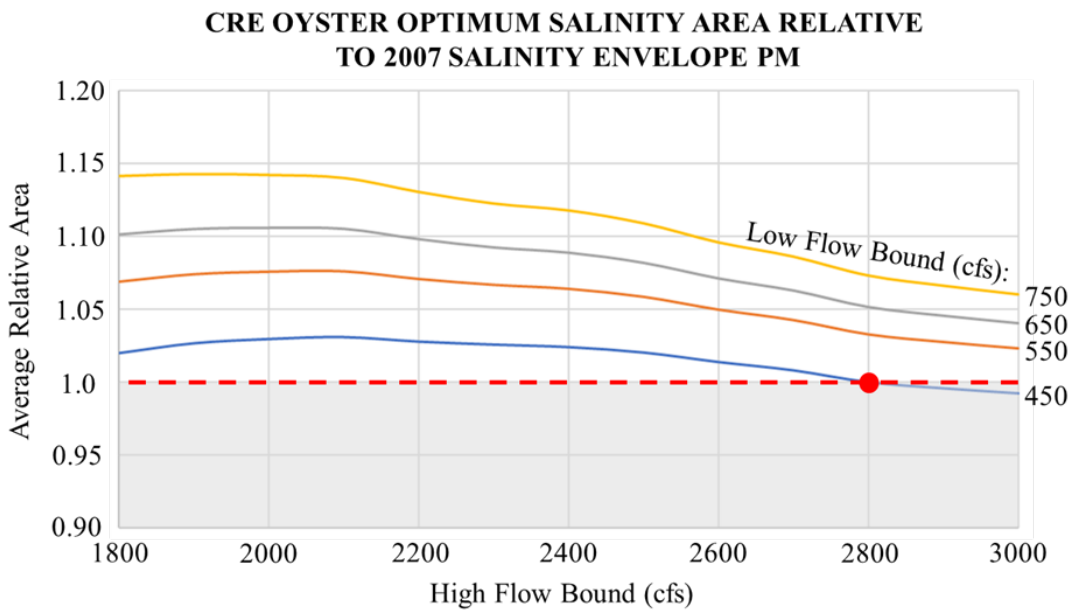

Figure 3. *Caloosahatchee Estuary (CRE) Eastern oyster Optimum Salinity (salinities 10–25) area, i.e., Potential Habitat Area (PHA) based on 14-day average salinity, relative to the CRE 2007 Salinity PM flow envelope (red dot: 450–2800 cfs, a score of 1.0 on the y-axis). High flow bounds represented on the x-axis; low flow bounds represented by colored lines labeled to the right of the plot. Flow Envelopes above the red dashed line/grayed area indicative of an improvement in PHA by 5, 10, 15, and 20%.*

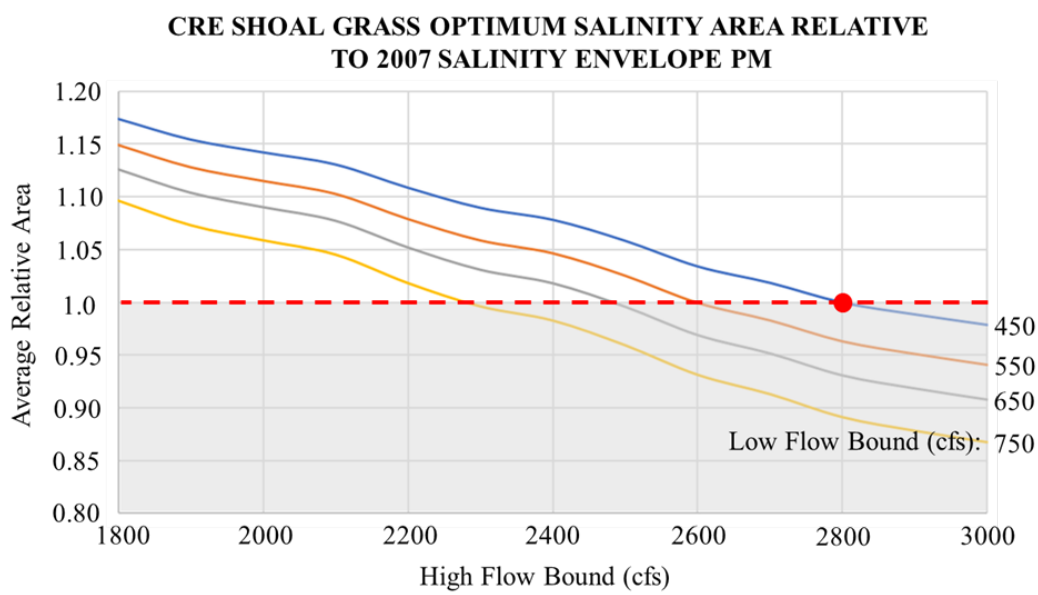

Figure 4. *Caloosahatchee Estuary (CRE) shoal grass Optimum Salinity (salinities 15–45) area, i.e., Potential Habitat Area (PHA) based on 14-day average salinity, for the shoal grass, relative to the CRE 2007 Salinity PM flow envelope (red dot: 450–2800 cfs, a score of 1.0 on the y-axis). High flow bounds represented on the x-axis; low flow bounds represented by colored lines labeled to the right of the plot. Flow Envelopes above the red dashed line/grayed area indicative of an improvement PHA by 5, 10, 15, and 20%.*

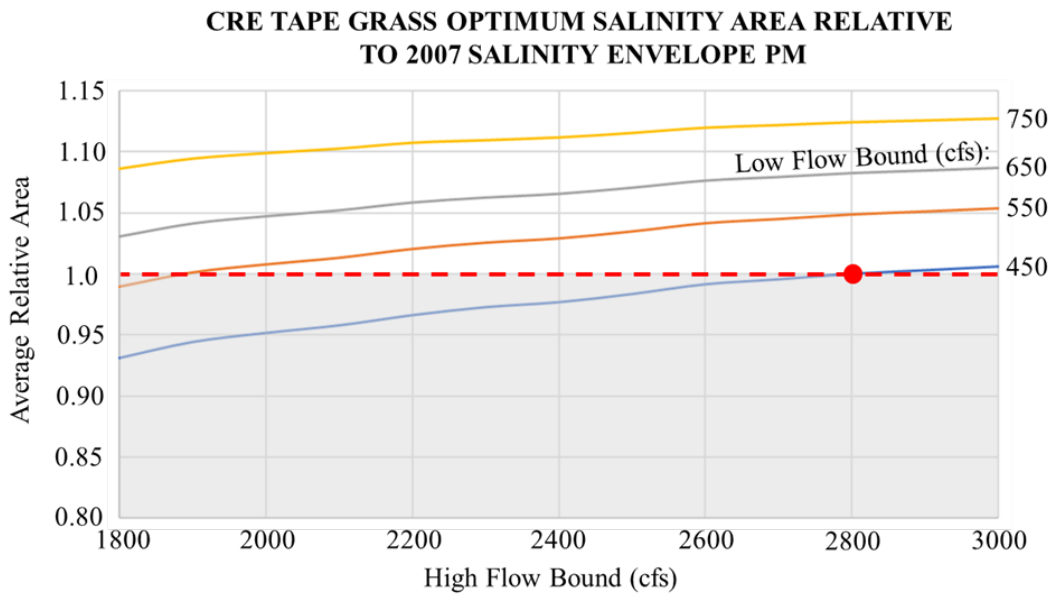

***Figure 5**. Caloosahatchee Estuary (CRE) tape grass Optimum salinities (<10) area for the tape grass, i.e., Potential Habitat Area (PHA) based on 14-day average salinity, relative to the CRE 2007 Salinity PM flow envelope (red dot: 450–2800 cfs, a score of 1.0 on the y-axis). High flow bounds represented on the x-axis; low flow bounds represented by colored lines labeled to the right of the plot. Flow Envelopes above the red dashed line/grayed area indicative of an improvement in PHA by 5, 10, and 15%.*

The plots for each of the three indicators (Figure 3–Figure 5) were compared to identify a Flow Envelope that "agreed" with each other among indicators; that is, those that showed maximum benefit across all indicators, while balancing the differing salinity regime requirements to support them in their respective regions within the estuary.

To mitigate the negative impacts to mesohaline and marine species downstream at higher high flow bounds, average PHA for tape grass should still see improvement if the low flow bound is greater than 550 cfs (Figure 5). Thus, flow envelope alternatives used for further evaluation for the CRE included low flow bounds no less than 650 cfs. For the high flow bound, high flows less than 2000 cfs and greater than 2400 cfs were not selected; this followed the logic that flows around or below 1800 cfs would decrease the potential benefit to tape grass in the upper CRE to <5% improvement (Figure 5), while those around or above 2400 cfs would steadily decrease the potential benefit to mesohaline and marine organisms in the lower CRE assuming higher low flow bounds were maintained for tape grass.

3 PERFORMANCE MEASURE POST-PROCESSING TOOLS

3.1 Methodology

In addition to the salinity maps generated for each Optimum Flow Envelope alternative (see main Documentation Sheet, Section 4), each were evaluated using PM post-processing tools (henceforth called "PM tools") used in CERP project alternative evaluation by the Interagency Modeling Center (IMC). The number of 14-day moving average (ma) and number of mean

monthly flow excursions outside the tested envelope bounds were counted against four current condition simulations in the Regional Simulation Model-Basins (RSB-BN) over a period of record 1965–2005 (Table 1). This exercise aimed to test that with the changes in hydrology per the implementation of new infrastructure and operations, including pre- and post-Lake Okeechobee Regulatory Schedule 2008, and several future scenarios that include the implementation of CERP projects (e.g., IRL-South; C-43 Reservoir), a positive impact on achieving the Optimum Flow Envelope in the estuaries is detectable based on for RECOVER System-wide Evaluation.

***Table 1**. Current condition simulations (period of record 1965–2005) available from the Regional Simulations Model-Basins (RSM-BN) through which the series of possible Optimum Flow Envelopes selected using Potential Habitat Area curves were evaluated.*

Condition Simulation (POR 1965–2005)	Simulation Description and Model Assumptions
ECB-WSE	Existing Conditions Base with Water Supply/Environment (WSE), the previous Lake Okeechobee Regulations schedule before LORS 2008, which had been in effect since 2000.
ECB-LORS2008	Existing Conditions Base with the current Lake Okeechobee Regulations schedule (LORS 2008). The 2008 LORS schedule objective is to manage lower lake elevations (compared to WSE) to reduce risk to the Herbert Hoover Dike and to lessen the likelihood of high damaging discharges to the Caloosahatchee River and St. Lucie Estuaries.
FWO-LORS2008	Future Conditions with the current Lake Okeechobee Regulations schedule called LORS2008. In general, the future projected conditions include, relative to existing conditions, additional representations of planned future project activities, including currently authorized State, Federal and Central Everglades Restoration Project (CERP) projects, e.g., Indian River Lagoon-South and C-43 Projects.
LOWRP+CEPP C240	Starts with FWO-LORS2008 simulation and adds the Lake Okeechobee Watershed project (LOWRP), an additional storage feature of approximately 46,000 acre-feet (ac-ft) north of Lake Okeechobee; and the EAA storage reservoir project (CEPP C240) which includes 240,000 ac-ft of storage south of the lake.

3.2 Results: Excursions Outside Optimum Flow Envelope Alternatives for Simulations

3.2.1 St. Lucie Estuary

Evaluating the four condition simulations (Table 1) using the 2007 Salinity Envelope Performance Measure (RECOVER 2007) flow targets for the SLE (350–2000 cfs), general trends depict improvement in the flow regime between existing condition simulations to future simulations with CERP project implementation (Figure 6). Both the number of mean monthly flow events below the salinity envelope (<350 cfs), and 14-day ma flow events above the salinity

envelope (>2000 cfs) decrease over time, with some differences among the four condition simulations.

Regional Simulation Model-Basins results for several flows were evaluated and similar trends are evident, indicating that changes in hydrology are detectable with project implementation (Table 2). At the low flow bounds tested, the number of monthly mean flow is <150 cfs from both basin runoff and Lake Okeechobee Regulatory Releases over the POR decrease by 100% (from 3 to 0 times); compared to the 2007 Performance Measure target of <350 cfs, which the number monthly mean flow <350 cfs decreased by 65% (from 97 to 34 times).

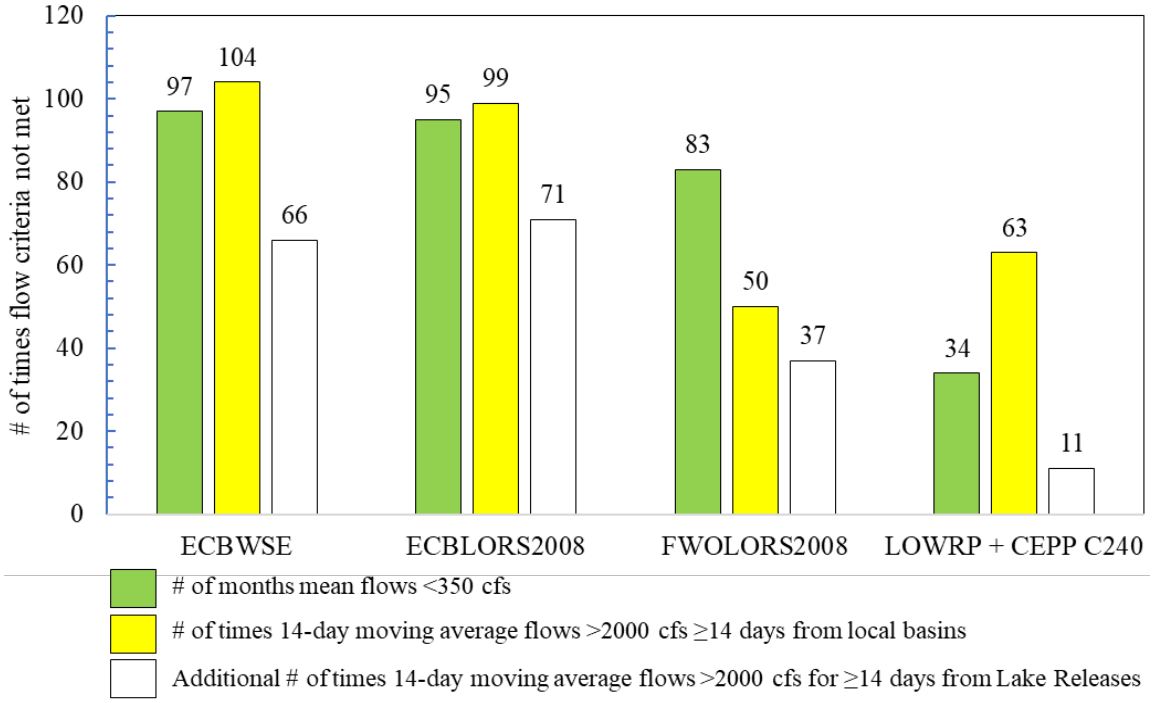

***Figure 6**. Number of times the 14-day moving average or monthly flows to the SLE fell below and above the 2007 Salinity Envelope (RECOVER 2007) of 350–2000 cfs between the four condition simulations, over the period of record (1965–2005).*

At the high flow bounds tested for this PM, notably, the contribution of Lake Okeechobee Regulatory Releases triggering excursions of 14-day ma flows greater than 1200, 1400, and 1600 cfs decrease by 88–91% from ECB-WSE and LOWRP+CEPP240 (Table 2). Flow excursions of 1200- 1600 cfs triggered by basin runoff were less with project implementations, but at lower percent differences. Of interest are the number of 14-day ma flows >1200 cfs triggered by basin runoff, compared to ECB-WSE, with a decreases of only 20% (from 252 for ECB-WSE to 201 times for LOWRP+CEPP240), whereas the number of 14-day ma flows greater than 1400, 1600, and 2000 cfs decrease by 33% (>1400 cfs) to 39% (>2000 cfs) in the LOWRP+CEPP240 condition simulation. This minimum change at >1200 cfs relative to the higher flows indicates that non-project related hydrological aspects of the system (i.e., hydrology of the basin and natural system, see USACE and SFWMD 2004 and information within) influence the occurrence of flows at this volume rather than CERP-related projects simulated in the RSM-BN model runs.

***Table 2**. Number of times over the 1965–2005 period of record in which 14-day moving average (ma) (# out of 1200 possible 14-day periods) or monthly mean (# out of 600 possible months) flows are observed for each condition simulation in the SLE and CRE; and percent difference from ECB-WSE for each the ECB-LORS2008, FWO-LORS2008, and LOWRP+CEPP240 runs. Those flows with asterisks (*) are flow conditions from the 2007 Salinity Envelope Performance Measure; all others are low or high flows from Optimum Flow Envelope alternatives.*

Estuary/ Flow (cfs)	Period	Source/ Triggered by	ECB-WSE	ECB-LORS2008	% difference from ECB-WSE	FWO-LORS2008	% difference from ECB-WSE	LOWRP +CEPP C240	% difference from ECB-WSE
SLE <150	Monthly Mean	Basin + Lake	3	3	0%	0	-100%	0	-100%
SLE <350*	Monthly Mean	Basin + Lake	97	95	-2%	83	-14%	34	-65%
SLE <150	14-day ma	Basin + Lake	12	12	0%	0	-100%	0	-100%
SLE <350*	14-day ma	Basin + Lake	185	185	0%	160	-14%	64	-65%
SLE >1200	14-day ma	Basin runoff	252	244	-3%	163	-35%	201	-20%
SLE >1400	14-day ma	Basin runoff	203	194	-4%	121	-40%	137	-33%
SLE >1600	14-day ma	Basin runoff	159	151	-5%	88	-45%	111	-30%
SLE >2000*	14-day ma	Basin runoff	104	99	-5%	50	-52%	63	-39%
SLE >1200	14-day ma	Lake Releases	105	72	-31%	54	-49%	9	-91%
SLE >1400	14-day ma	Lake Releases	93	76	-18%	56	-40%	10	-89%
SLE >1600	14-day ma	Lake Releases	86	83	-3%	48	-44%	10	-88%
SLE >2000*	14-day ma	Lake Releases	66	71	8%	37	-44%	11	-83%
CRE <450*	Monthly Mean	Basin + Lake	180	116	-36%	23	-87%	37	-79%
CRE <650	Monthly Mean	Basin + Lake	209	198	-5%	217	4%	260	24%
CRE <750	Monthly Mean	Basin + Lake	220	213	-3%	241	10%	276	25%
CRE >2000	14-day ma	Basin + Lake	146	133	-9%	103	-29%	81	-45%
CRE >2200	14-day ma	Basin + Lake	129	122	-5%	90	-30%	66	-49%
CRE >2400	14-day ma	Basin + Lake	112	112	0%	79	-29%	61	-46%
CRE >2800*	14-day ma	Basin + Lake	96	94	-2%	70	-27%	54	-44%
CRE >2000	14-day ma	Basin runoff	154	146	-5%	133	-14%	116	-25%
CRE >2200	14-day ma	Basin runoff	134	130	-3%	117	-13%	95	-29%
CRE >2400	14-day ma	Basin runoff	118	114	-3%	97	-18%	79	-33%
CRE >2800*	14-day ma	Basin runoff	86	84	-2%	63	-27%	57	-34%
CRE >2000	14-day ma	Lake Releases	95	96	1%	40	-58%	16	-83%
CRE >2200	14-day ma	Lake Releases	88	86	-2%	39	-56%	16	-82%
CRE >2400	14-day ma	Lake Releases	80	91	14%	36	-55%	13	-84%
CRE >2800*	14-day ma	Lake Releases	67	90	34%	42	-37%	15	-78%

3.2.2 Caloosahatchee River Estuary

Evaluating the four condition simulations using the 2007 Salinity Envelope Performance Measure (RECOVER 2007) flow targets for the CRE (450–2800 cfs), general trends depict improvement in the flow regime between existing condition simulations to future simulations with CERP project implementation (Figure 7). Both the number of mean monthly flow events below the salinity envelope (<450 cfs), and 14-day ma flow events above the salinity envelope (>2800 cfs) decrease between scenarios, with some differences among condition alternatives.

At the low flow bounds tested for this PM, the number of monthly mean flows from both basin runoff and Lake Okeechobee Regulatory Releases that are <750 cfs increase under future simulations by 10% (FWO-LORS2008) and 25% (LOWRP+CEPP240) relative to ECB-WSE simulations, while mean monthly flows <450 cfs decrease by nearly 80% between ECB-WSE and LOWRP+CEPP240. These results reflect the fact that current CERP projects with which model runs are conducted were formulated with the 2007 Salinity Envelope Performance Measure low flow bound of 450 cfs in mind. The updated Salinity PM flow envelope should be taken into consideration regarding future approaches or modifications to the project planning process.

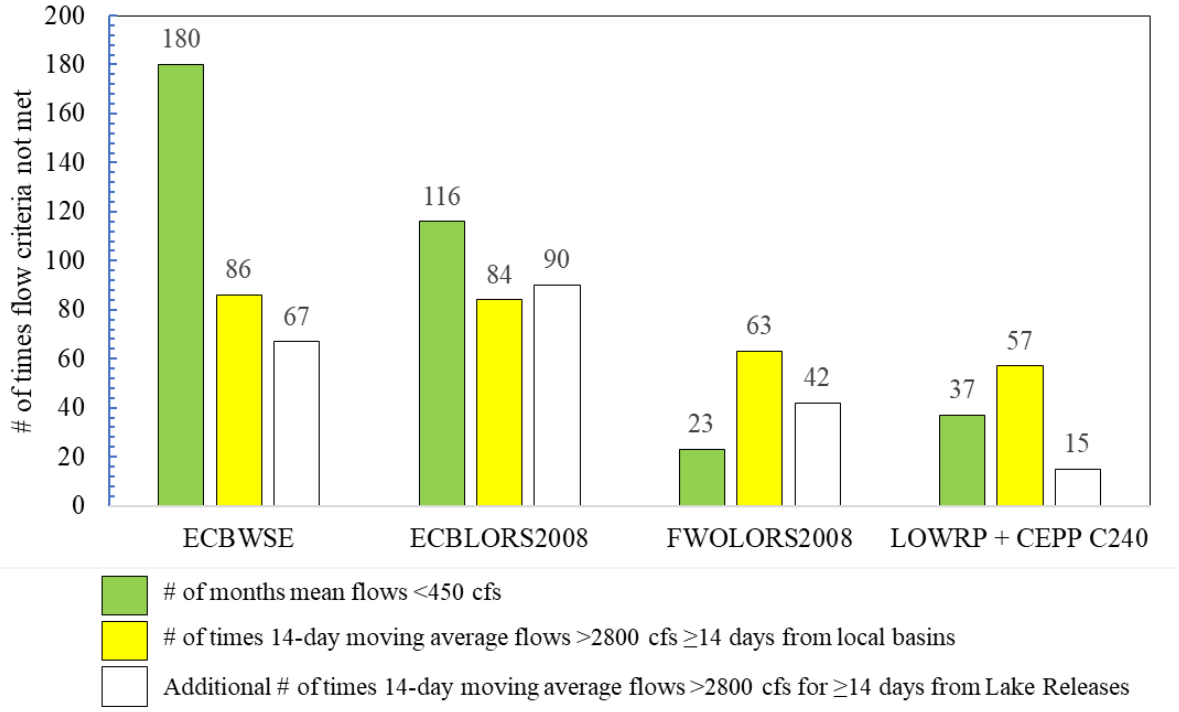

***Figure** 7. Number of times the 14-day moving average or monthly flows to the CRE fell below and above the 2007 Salinity Envelope (RECOVER 2007) of 450–2800 cfs between the four condition simulations, over the period of record (1965–2005).*

At the high flow bounds tested, notably, the contribution of Lake Okeechobee Regulatory Releases triggering excursions of 14-day ma flows greater than 2000, 2200, and 2400 cfs decrease by 82–84% between ECB-WSE and LOWRP+CEPP240 (Table 2). These flow

excursions triggered by basin runoff were also less, but at smaller percentages with project implementation scenarios (25%–33%).

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APPENDIX C: Science in Support of the RECOVER Northern Estuaries Program and Performance Measure Development

1 HYPOTHESIS CLUSTERS

The MAP 2009 (RECOVER 2009) science strategy included the development of hypothesis clusters. Hypothesis clusters address the integration of the important stressor-response elements contained within a conceptual ecological model (CEM) to better capture and represent the complex stress or response relationships of the system (RECOVER 2006a; 2006b). A further benefit to the development of hypothesis clusters was the refinement in the types and numbers of Performance Measures (PMs) and metrics and their linkage to Interim Goals (RECOVER 2005). Salinity is a "stressor" in all the NE Hypothesis Clusters.

The ecological premise that underlies all CERP hypotheses in the NE is that prior to water management (i.e., landscape alteration and post inlet construction), natural landscapes, which included extensive, isolated wetlands, acted as a buffer and provided more natural patterns of freshwater inflow to the NE and sustained an ecologically appropriate range of salinity conditions with fewer high and low salinity extremes.

Water Quality CERP Hypothesis: The construction and operation of water storage and treatment facilities in the NE regions will improve the quantity, quality, and timing of flows into the estuaries, which will in turn provide a salinity envelope that avoids ecologically damaging high and low salinity extremes.

Oyster Health and Abundance CERP Hypothesis: Restoration of more natural freshwater inflows by retention of water in reservoirs, wetland rehydration, and changing delivery patterns; removal of fine-grained sediment; and introduction of artificial substrate into South Florida estuaries (all results of CERP implementation) should provide beneficial salinity and habitat conditions that promote the re-establishment of healthy Eastern oyster (*Crassostrea virginica*) beds. Detailed working hypotheses relating to oyster health and abundance can be found in the SSR 2006 (RECOVER 2006b).

Submerged Aquatic Vegetation CERP Hypothesis: The relationship between freshwater dynamics and SAV is complicated with outcomes dependent on the quantity, quality, and timing of freshwater releases coupled with the salinity requirements of individual species, ranging from freshwater-to-polyhaline, and their associated communities. In addition to the main hypotheses, a series of sub-hypotheses have been developed for use in understanding the synergistic nature of water delivery and SAV populations; these can be found in the Assessment Strategy 2006 for the MAP (RECOVER 2006a).

Benthic Infauna CERP Hypothesis: Benthic infauna are important indicators of water and sediment quality and are used to assess overall estuarine health and follow long-term trends in estuarine communities related to anthropogenic impacts. By examining shifts in the community and relating them to water management practices as depicted in the CEM, it is possible to obtain an understanding of the major environmental processes affecting the biota. This monitoring

program can identify discrete zones in the estuary by community type, and rapidly identify and predict responses to flows. More details on the hypothesis cluster associated with infauna can be found in the MAP Part 2 (RECOVER 2006a).

Fisheries CERP Hypothesis: Several water quality/flow dynamics hypotheses have been developed and are described in detail in the MAP Part 2 (RECOVER 2006a). These hypotheses have been tested using several different technologies. Small fish and early developmental stages of larger species are more sensitive to adverse environmental conditions and therefore suffer the highest mortality rates. Many aspects of spawning, larval movement and development, juvenile growth, and predation have been directly linked to freshwater flow patterns.

1.1 Monitoring

MAP monitoring in the Northern Estuaries is based on the CEMs (Section 4.3 in the main Performance Measure Documentation Sheet) and Hypothesis Clusters. Oyster, SAV, and benthic infauna monitoring are currently being used to assess the status of the system and will be used to assess the progress of CERP as projects come online. The RECOVER System Status Report (SSR; published every five years) documents the measurement of ecological indicators and their application to assess conditions in the Everglades ecosystem. This information provides feedback to decision-makers on the ecological response to past restoration activities and informs the timing of planning for CERP projects yet to be implemented. This report also informs adaptive management actions and identifies uncertainties that need further study to assure restoration success.

2 HABITAT SUITABILITY INDEX MODELS

In support of the current update to RECOVER Interim Goals (due late 2020), quantitatively validated, GIS-based oyster habitat suitability index (HSI) models for the SLE and CRE were updated. Layers include salinity, temperature, and substrate type. HSI model outputs were first validated spatially using live oyster density data available from RECOVER monitoring data. A study by Chen et al. (*in prep*) showed that HSI values were significantly correlated with live oyster density in the CRE. HSI values <0.5 accurately indicated unsuitable habitat conditions where near zero live oyster density was observed. Both correlation and time series analyses suggest that the derived HSI output is a robust and accurate indicator of oyster habitat suitability in the estuary.

3 MAPPING

Throughout the implementation of CERP, RECOVER aims to understand how flow and salinity conditions affect the Northern Estuaries over time by mapping the extent of oysters and SAV. If conditions in one location are no longer suitable for survival, organisms will settle and develop in other areas suitable to their physiological tolerances. Over time, scientists can capture change in environmental suitability by observing changes in oyster and SAV distribution as implementation of CERP projects progress. While monitoring of oyster reef and SAV health has taken place since the late 1990s in many of the subject estuaries, the extent and coverage of oyster reefs, SAV, and their current distribution in the estuaries requires updating every few years. Mapping these areas is essential since the spatial location, health, and bottom types (e.g.,

sand, shell, silt, etc.) inhabited by oyster and SAV resources influences the natural expansion of those resources and the success of restoration activities. A detailed benthic habitat and substrate characterization mapping project for the Northern Estuaries was completed in 2011 (Dial Cordy and Associates Inc. 2011). The map products include habitat type (e.g., oyster reef and SAV) and substrate type throughout each of the estuaries including the Loxahatchee River Estuary and Lake Worth Lagoon. The estuaries were mapped in all areas up to the 9-foot bathymetric contour using side-scan sonar technology.

Oyster mapping produces an overall picture of oyster bed extent and is used to track landscape and patch-scale changes in oyster reef distribution. Since 2000, RECOVER has conducted routine monthly and quarterly *in situ* monitoring of oysters in the Northern Estuaries that includes density, disease prevalence and intensity, reproductive development, and juvenile recruitment, growth, and survivorship. Combined with mapping, these fitness indices improve our understanding of the overall condition of oysters in the region and how changes in the environment over time may trigger shifts in community structure and distribution. Re-mapping of these estuaries should occur approximately once every five (5) years as restoration efforts progress. The SLE and CRE were mapped again in 2019 (results and final deliverables pending) and the final map will be used to evaluate the best approach for continued mapping of oyster and other resources in the Northern Estuaries moving forward.

4 FUTURE TOOL DEVELOPMENT AND NEEDS

4.1 Duration and Return Frequency of Salinity/Flow Excursions

The CERP adage of "getting the water right" includes hydrologic restoration to improve the quantity (i.e., volumes of inflow in cfs), quality (i.e., salinity envelope), and timing (i.e., duration, return frequency, and seasonality) of freshwater inflows to the Northern Estuaries. The duration and return frequency of excursions outside the Optimum Salinity and Flow Envelopes are addressed to a degree (Section 3 in the main Performance Measure Documentation Sheet) based on supported data and deemed ecologically relevant to salinity stress and ecological indicator responses from past monitoring. Changes from the 2007 Salinity Envelope PM include the period in which target events are defined: namely, the modeled flows are over a 14-day moving average rather than a monthly mean for low flow targets in the SLE and all flow targets in the CRE.

The issue of duration, return frequency, as well as recovery periods of tolerable and optimum salinities for ecological indicator species, are further addressed in ongoing and planned studies (Section 4.3 and Section 4.4) whose results are expected to inform future revision of these targets.

Additional work is also necessary to establish targets for contributions of inflow from each estuary's watershed compared to Lake Okeechobee Regulatory Releases, and how to deal with "watershed-triggered" or "Lake Okeechobee-triggered" events. For example, supposing inflows from runoff in the SLE watershed is near but below the Optimum Flow Envelope high flow bound (e.g., 1350 cfs), and there are Lake Okeechobee Releases of 100 cfs, this would result in 1450 cfs, an excursion from the Optimum Flow Envelope by 50 cfs; this would be designated a Lake Okeechobee-triggered event. How to account for these events, and what relative

contributions are acceptable from each source of freshwater needs to be addressed in future updates.

Finally, further modeling is needed to determine impacts of SLE Damaging Flows to the S-IRL and the Atlantic nearshore environment, and CRE Damaging Flows to San Carlos Bay and the Gulf of Mexico. These may be included as part of the Lake Okeechobee System Operating Manual (LOSOM) update. Where applicable, an addendum to this Salinity Envelope PM will be made to reflect the results of this additional modeling.

4.2 Climate Change and Sea-Level Rise

Future efforts need to directly address climate change, sea level rise (SLR), and increasing sea surface temperature (SST) projections in predictive modeling. El Niño Southern Oscillation (ENSO) events are inherently captured in the observed flows from the period of record used to model flow alternatives in this Salinity Envelope PM, but a more explicit approach to incorporating SLR boundary conditions into the CH3D hydrodynamic salinity model is warranted. It is expected that future SLR would influence salinity envelopes and provide an opportunity to study how flow regime would change to satisfy salinity criteria. Finally, increasing SST may act as a confounding variable affecting oyster populations as it relates to spawning periodicity and the combined stressors and interactive effects of temperature and salinity on oyster disease.

4.3 Ecological Models to Support RECOVER Tools and PMs

In addition to the oyster HSI model (Section 2) used for RECOVER Interim Goals, HSI models are currently in development for SAV species tape grass (*Vallisneria americana*) and shoal grass (*Halodule wrightii*) for the Northern Estuaries. One of the key drivers for SAV distribution and density is light availability, which is not addressed in this Salinity Envelope PM. Due to its importance, photosynthetically-active radiation (PAR) measurements and light attenuation coefficient calculations have been introduced to the updated RECOVER Northern Estuaries SAV Ecosystem Assessment (NESEA) program (Kahn 2019).

The oyster and SAV HSI models should be used to create updates for Northern Estuaries Oyster and SAV PMs. Other ecological models with more mechanistic approaches to evaluate and assess CERP activities such as those in Buzzelli et al. (2015) should also be further developed for these species-specific PMs by simulating ecosystem-level processes of freshwater inflow, salinity, light, and other environmental and biological parameters affecting estuarine ecology.

4.4 Ongoing Studies

4.4.1 Duration and Return Frequency of Salinity Excursions and Recovery Time for the Eastern Oyster

Regarding the need to better define the responses of ecological indicators to duration and return frequency of excursions outside the Salinity/Flow Envelope, the South Florida Water Management District (SFWMD) has an ongoing two-year contract with Florida Gulf Coast University and the University of North Carolina Wilmington to conduct a series of iterative

mesocosm experiments exposing adult and spat Eastern oyster (*C. virginica*) to varying durations and return frequencies of stressful and damaging salinities (0–5), as well as duration at varying "recovery" salinities to simulate pulse release conditions and under different temperatures to reflect seasonality. The objective of the study is to generate data and decision support tools to inform water management operations when releases to the Northern Estuaries are deemed necessary. While driven especially for weekly operations, understanding the various tolerances of adult and spat oysters to volumes of freshwater inflows capable of reducing salinities of 0–5 for a given period can inform biological models used in setting PM targets. For example, it is expected that conclusions from this mesocosm study will inform hydrologic targets for consecutive excursion events and their durations can be refined in the next Salinity Envelope PM revision.

The first study hypothesis is that oysters will yield a higher probability of survival if high volume discharges (i.e., low salinities) are pulsed and interspersed with recovery periods of lower volume discharges (i.e., higher salinities). This is based on the premise that oysters may recover by opening their valves to eliminate waste, feed, and respire when tolerable salinities are available during these recovery periods. It is also hypothesized that longer recovery times between multiple exposure pulses will yield higher survival, and finally, that oysters will yield a higher probability of survival under low salinity conditions when temperatures are also lower (i.e., spring and winter, 18–24°C) compared to higher temperatures (i.e., summer and fall, ~30°C).

The mesocosm exposures should determine the effect of specific freshwater inflow regimes. Understanding the additive effect of temperature on tolerance of salinity is especially important during the summer rainy season when temperatures are elevated along with increased natural freshwater inflows. The results from the mesocosm experiments will expand on previous experimental results in peer-reviewed literature to provide a greater understanding of how inflows can be sustainably managed for Northern Estuaries oysters. One of the mesocosm study deliverables will include a "decision tree" (i.e., interactive flowchart) which can be used by water managers to assess ecological risks to oysters under different life history conditions (e.g., larvae or spat at settling stage, juveniles, adults beginning gametogenesis) across a wide range of salinities, and give recommendations to alternative inflow regimes.

4.4.2 Use of Biomarkers to Examine Salinity Stress in Tape Grass and Rangia Clam

A study by SFWMD Coastal Ecosystems scheduled to begin in early 2020 will further evaluate stress responses of both tape grass and the Rangia clam (*Rangia cuneata*) clam in mesocosm experiments using physiological biomarkers. The Rangia clam is a bivalve found in the mid-to-upper region of the CRE, a region which routinely experiences lower salinities and provides habitat for brackish to freshwater organisms (LaSalle and de la Cruz 1985; Wakida-Kusunoki and MacKenzie 2004; Wong et al. 2010). Measurement of physiological biomarkers provides a rapid and sensitive method of assessing the health of an organism and its stress responses. These responses can include protein accumulation, tissue nutrient or pigment concentration changes, or upregulation of antioxidant compounds. In both plants and animals, the generation of reactive oxygen species (ROS) occurs naturally and continuously during aerobic metabolism. Antioxidant systems are in place to detoxify and eliminate ROS. Changes in these antioxidant response

mechanisms in marine organisms, including SAV and clams, have been observed as a result of salinity stress (Solé et al. 1999; Apel and Hirt 2004; Miller et al. 2010; Lauer et al. 2011; Carregosa et al. 2014). In SAV, osmoregulatory stress can also trigger changes in antioxidant carotenoid pigment compounds and affect chlorophyll *a* and *b* pigments (Thorhaug et al. 2006; Lauer et al 2011; Trevathan et al. 2011). The use of biomarkers such as antioxidant enzyme assays can be a vital tool in monitoring programs (Goldberg et al 1975; Obrea et al. 2002).

The goal of the SFWMD mesocosm study is to understand stress responses of tape grass and Rangia clam to various salinity regimes (salinity treatments 0–18). Data gaps exist regarding an invertebrate benthic ecological indicator in the low salinity regions of CRE and in tape grass responses at the higher end of their salinity stress maxima. Unlike the physical metrics of presence/absence or density, physiological biomarkers provide a more sensitive assessment of organismal health to both short-term and chronic exposure to stressful environmental conditions, such as hypersalinity or hyposalinity. These mesocosm studies will be designed to examine multiple biomarkers in each organism under various ecologically relevant salinity regimes. RECOVER can further refine hydrologic targets for this and other PMs.

4.5 Ecological Indicator Species

Other ecological indicator species may be of interest to the RECOVER Northern Estuaries Program depending on new science within and external to RECOVER.

Previous MAP contracts in the Northern Estuaries included fisheries monitoring, although other agencies such as the Florida Fish and Wildlife Conservation Commissions Fish and Wildlife Research Institute (FWRI) continues seining and acoustic telemetry in the SLE and monitoring endangered smalltooth sawfish (*Pristis pectinata*) in the CRE. The way in which high freshwater inflows affect fish populations is of interest to RECOVER partners, managers, many stakeholder groups, and the public. Questions of inflow regime, estuarine geomorphology, and availability of habitat on local fish populations and their movements and responses to inflows could provide a useful addition to the suite of indicators for the Northern Estuaries dependent on study results. The RECOVER Southern Coastal Systems Program includes a Performance Measure for juvenile spotted seatrout (*Cynoscion nebulosus*) habitat quality (i.e., HSI) (RECOVER 2017).

Two Northern Estuaries projects with FWRI were identified and contracted by the SFWMD in late 2019 to analyze a backlog of seine sampling data from the St. Lucie Estuary (SLE) and Loxahatchee River Estuary (LRE), and to collect and analyze acoustic telemetry data of several large-bodied fishes in the SLE and Southern Indian River Lagoon including the spotted seatrout, common snook (*Centropomus undecimalis*), fat snook (*C. parallelus*), sheepshead (*Archosargus probatocephalus*), and goliath grouper (*Epinephelus itajara*). This project is leveraged by the FACT Network, a grassroots collaboration between marine scientists using acoustic telemetry and other technologies to track fish and sea turtles, which originated as the Florida Atlantic Coastal Telemetry Network but now includes partners from the Bahamas to the Carolinas (FACT Network 2019). The results may support reintroducing fisheries monitoring to the Northern Estuaries RECOVER monitoring program. Final deliverables for the seine data analysis and acoustic telemetry are due September 2020 and September 2021, respectively.

In addition, several sample sites included in the benthic infauna monitoring in the SLE and S-IRL have been backlogged: the samples are collected but not analyzed. A SFWMD contract was initiated in late 2019 to analyze these 216 backlogged samples. New to the benthic infauna monitoring program, genetic barcoding and representative photographs of each of 40 key invertebrate taxa will also be sent to taxonomists for conclusive morphological identification to develop a benthic infaunal database. This effort will be critical to identifying taxa tolerant to freshwater inflows and salinity excursions. Final deliverables for the sample processing and genetic barcoding is due in December 2020.

Finally, there are several suitable indicators of high flows (i.e., oysters and meso/polyhaline-adapted SAV), but only one SAV as an indicator of low flows (i.e., tape grass); the Rangia clam is a potential new indicator for low flows in the Northern Estuaries (Section 4.4.2). Additional indicators of low flow should be considered as new science becomes available.

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