APPENDIX G
LOCAR BENEFIT MODEL

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G LAKE OKEECHOBEE COMPONENT A RESERVOIR BENEFIT MODEL

This appendix describes the documents and methodology used to quantify the ecological benefits and support plan evaluation, comparison, and selection for the Lake Okeechobee Component A Storage Reservoir (LOCAR or Project).

G.1 Model Documentation

The Department of the Army ER 1105-2-100, "Planning Guidance Notebook," requires that ecosystem restoration planning contribute to national ecosystem restoration (NER), which is measured in terms of increases in the net quantity and/or quality of desired ecosystem resources. The U.S. Army Corps of Engineers (Corps) uses NER benefits as the basis to compare alternatives and select plans for ecosystem restoration projects. The LOCAR planning model builds on previous planning models that underwent peer review per EC 1105-2-412, "Assuring Quality of Planning Models" and applies similar performance metrics. Habitat benefits were calculated by applying output from the regional hydrologic model, the Regional Simulation Model Basins (RSM-BN) (Section G.2.2), to the performance measures in Attachments G-1 and G-2.

G.2 Overview

The LOCAR planning model was specifically developed to evaluate Project alternatives for an aboveground storage reservoir used to store water that would otherwise go into Lake Okeechobee. The primary areas to be evaluated include Lake Okeechobee and the St. Lucie River and the Caloosahatchee River and Estuary (Northern Estuaries). The planning model was developed by South Florida Water Management (SFWMD) staff and the Jacksonville District Corps with support from multiple federal, state, and local agencies including the U.S. Fish and Wildlife Service (USFWS), U.S. Environmental Protection Agency (EPA), Florida Fish and Wildlife Commission (FWC), Florida Department of Environmental Protection (FDEP), Natural Resources Conservation Service (NRCS), Lee County, and Martin County. Members of the LOCAR Project team include Lake Okeechobee and estuary flora and fauna subject matter experts with extensive experience working in South Florida and Everglades wetland systems in the fields of ecology, hydrology, engineering, and planning.

Performance measures (PMs) were used to document the linkages between hydrologic output from models and ecosystem functions to evaluate the degree to which alternative plans met restoration objectives. Each of the PMs was updated from the prior Lake Okeechobee Watershed project based on the availability of new tools, changes to the landscape, updated knowledge on the system from peer-reviewed literature and technical reports, and Restoration, Coordination, and Verification (RECOVER) review comments. RECOVER is the interagency system-wide science team that supports Comprehensive Everglades Restoration Plan (CERP) projects. It is made up of Everglades scientists independent of the Project team. Several of the Project PMs for the planning effort were derived from those PMs approved for use in CERP by RECOVER. Each PM has a predictive target or comparable performance scores and process for how to measure the predicted performance of alternatives. Targets were based on peer-reviewed relationships between hydrology and ecological species or communities and technical synthesis reports of multiple data sources identifying restored conditions in Lake Okeechobee and the St. Lucie and Caloosahatchee Estuaries. PM scores were displayed as a function of restoration potential or achievement of the target. Habitat unit (HU) scores were produced by indexing the scores. The indexed scores were then multiplied by their proportion of the total index score for a given ecological zone and multiplied by the area to get the HUs. HUs are then evaluated for the existing conditions baseline (ECB), Future Without Project (FWO) condition, and Project alternatives to identify the best performer for each zone and the combined area.

G.2.1 Description of Project Performance Measures

Three PMs were developed to measure two study objectives (**Table G-1**) for two ecological zones (**Table G-2**):

1. **PM 1 Lake Okeechobee**–Hydrologic regimes in Lake Okeechobee specific to two criteria: 1) Lake stage envelope and 2) Extreme high and low lake stage.
2. **PM 2 Caloosahatchee Estuary Salinity**–Freshwater inflows to manage salinity in the Caloosahatchee Estuary to benefit native flora and fauna.
3. **PM 3 St. Lucie Estuary Salinity**–Freshwater inflows to manage salinity in the St. Lucie Estuary to benefit native flora and fauna.

The complete RECOVER-approved PM Documentation Sheets are located in **Subsection G.8**.

Table G-1. Study Objectives Linked to PMs.

Objective	PM 1 - Lake Okeechobee Stage	PM 2 – Caloosahatchee Estuary Salinity	PM 3 – St. Lucie Estuary Salinity
Improve timing and distribution of flows into Lake Okeechobee to maintain ecologically desired lake stage ranges.	Yes	N/A	N/A
Reduce flows from Lake Okeechobee to improve the salinity regime and the quality of oyster, submerged aquatic vegetation (SAV), and other estuarine community habitats in the Northern Estuaries.	N/A	Yes	Yes

Table G-2. Ecosystem Zones Linked to PMs.

Ecosystem Zones	PM 1	PM 2	PM 3
Lake Okeechobee	**Yes**	**Yes**	N/A
Estuaries–Oysters	N/A	**Yes**	**Yes**

G.2.2 Hydrologic Models Used

Several hydrologic modeling tools were used to provide the output used in PMs 1, 2, and 3. Each of the PMs has defined metrics and targets. The PMs are hydrologic metrics based on output from a regional hydrologic model—the Regional Simulation Model Basins (RSM-BN). This model was developed by the SFWMD Hydrology and Hydraulics Bureau. These models provided daily, detailed estimates of hydrology across the 52-year period of record (January 1965 to December 2016) and were used to evaluate system responses to Project alternatives.

The RSM-BN is a link-node model designed to simulate the transfer of water from a pre-defined set of watersheds, lakes, reservoirs, or any waterbody that receives or transmits water to another adjacent waterbody. The model domain covers Lake Okeechobee and four major watersheds related to the northern portion of the Project Area: Kissimmee River, St. Lucie River, Caloosahatchee River, and Everglades Agricultural Area (EAA).

Model output was maintained in a data access, storage, and retrieval system managed by the SFWMD and Corps under the CERP Information and Data Management Program. Output for each PM sub-metric was provided in a comma-separated-value (csv) format with charts and graphics to aid in the assessment of restoration benefits.

PM targets were primarily based on output from the Natural System Model version 4.6.2 (NSM), which simulates the hydrologic response of a pre-drained Everglades. The NSM has been used as a planning tool in several Everglades restoration projects. Additional documentation of NSM can be found at https://www.sfwmd.gov/science-data/nsm-model.

The hydrologic models referenced, RMS-BN, have gone through the Corps Engineering Model Certification process established under the Engineering and Construction (E&C) Science and Engineering Technology (SET) initiative (Section G-6).

G.2.3 Spatial Extent of the Benefited Area

The Study Area includes Lake Okeechobee (PM 1; **Figure G-1**) and the Northern Estuaries (Caloosahatchee [PM2; **Figure G-2**] and St. Lucie [PM3; **Figure G-3**]).

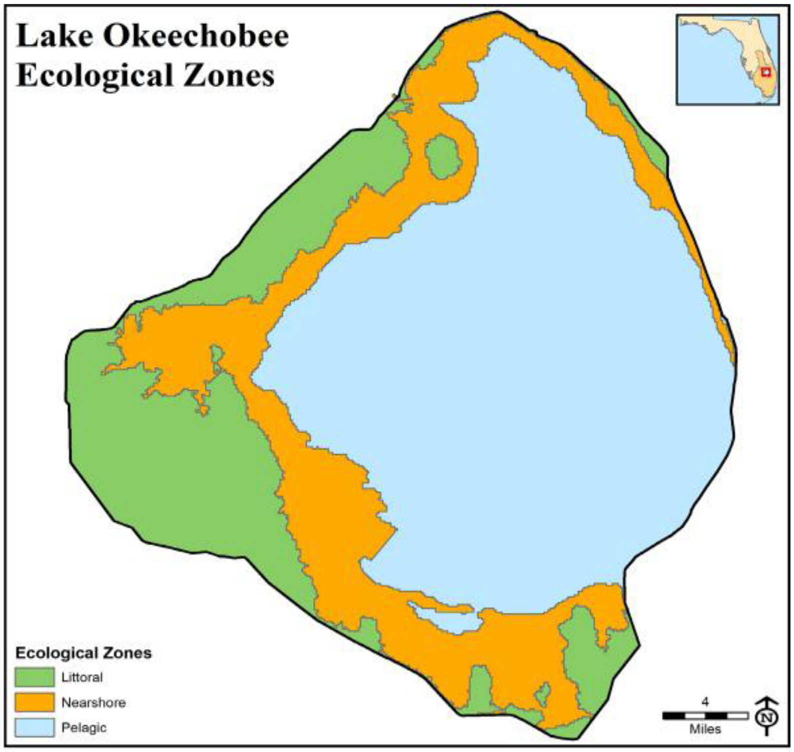
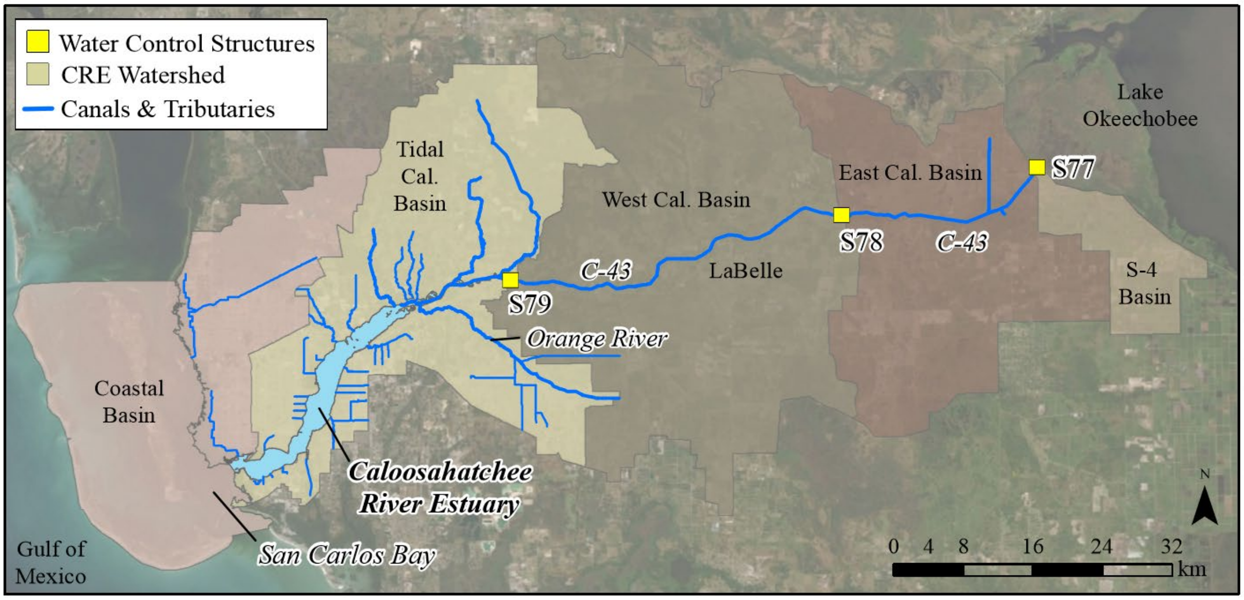
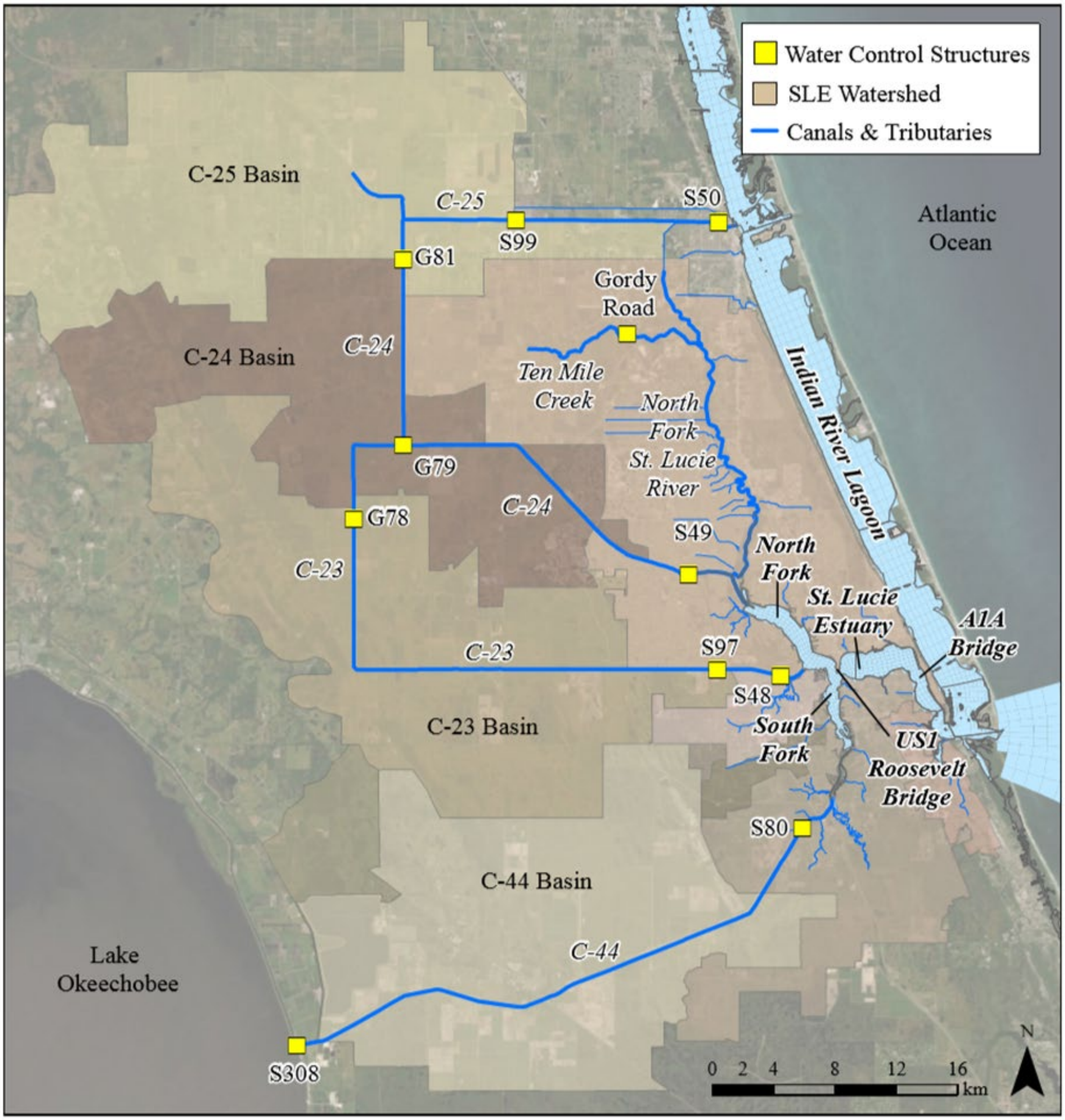


Figure G-1. Littoral, nearshore, and pelagic (limnetic) habitats in Lake Okeechobee (450,000 acres total).



Note: Oyster habitat in the Caloosahatchee River and Estuary (CRE) for use in benefits analysis is 980 acres (map from RECOVER 2020).

Figure G-2. Caloosahatchee Estuary Watershed, connections to Lake Okeechobee and tributaries, and water control structures.



Note: Oyster habitat in the St. Lucie River and Estuary (SLE) for use in benefits analysis is 434 acres (map from RECOVER 2020).

Figure G-3. St. Lucie Estuary Watershed, connections to Lake Okeechobee and tributaries, and water control structures.

G.3 Lake Okeechobee Benefit Calculations

This section describes the HU calculations for Lake Okeechobee.

G.3.1 Lake Okeechobee Performance Measures

This subsection provides a brief description of the Lake Okeechobee PMs, including the target(s) for each, and the applicable metrics for the target(s).

G.3.1.1 PM 1.1 – Lake Okeechobee Stage Envelope Performance Measure

Historically, littoral marshes of Lake Okeechobee expanded well outside the current footprint of the lake, with high-water events pushing the lake laterally into short-hydroperiod wetlands in the surrounding watershed. Since construction of the levee (Herbert Hoover Dike), littoral marshes are restricted within the lake's current footprint. If lake stages are managed too high, the entire marsh retreats upslope, extirpating shorter hydroperiod wetlands at high elevations. If lake stages are managed too low, high elevation marshes transition to terrestrial communities, and the entire marsh moves downslope. Currently, the littoral marsh generally occupies elevations from the base of the surrounding levees (15.0 feet [ft] National Geodetic Vertical Datum of 1929 [NGVD29] to approximately 12.0 ft NGVD29 in elevation) (Havens 2002), although fringing stands of bulrush and aquatic grasses can extend to around 10.0 ft in elevation (Graham et al. 2020), and beds of submerged vegetation to 8.0 or 9.0 ft, when conditions allow (Havens et al. 2004). Lake stage has a profound effect on the health of these littoral marshes and the lake in general (Havens 2002), not just due to direct hydrologic relationships, but to the varying connectivity of the central, muddy portion of the lake with littoral and nearshore areas at different lake stages (Havens 1997). Seasonally variable water levels within the range of 12.0 ft (NGVD29) as a June to July low and 15.0 ft (NGVD29) as a November to January high have been supported by numerous studies (Johnson et al. 2007, Havens and Gawlik 2005, Havens 2002) as the best tradeoff between wet and dry conditions on the lake, supporting short- to long-hydroperiod communities and capturing key parameters. In order to establish seasonal targets and allow for inter-annual variation, an ecological envelope was created by establishing transitions to these high and low targets and adding a buffer; first in 2007 (RECOVER 2007) and then updated in 2020 (RECOVER 2021). The resulting envelope is a 12.0 ft to 15.0 ft seasonally variable stage, ranging from 14.5 to 15.5 ft in the winter and from 11.5 to 12.5 ft in the summer.

This PM is based on the amount of time lake stage remains within the desired envelope of 11.5 to 15.5 ft, and good performance should result in an increase in spatial extent of bulrush along the western lakeshore; increased spatial extent of spikerush, beakrush, willow, and other native plants in the littoral zone; increase in spatial extent of vascular submerged plants; a shift in taxonomic structure of zooplankton to better support fishery resources; an increase in diversity, distribution, and abundance of forage fish in the littoral and nearshore zones; and an increase in the use of the littoral zone for wading bird foraging and nesting.

Recovery from extreme high lake stage events can be expedited with low lake stages, as documented for submerged plants (Havens et al. 2004, Jin and Ji 2013) and for sport fish (Havens et al. 2005). Most evidence of recovery has been from extreme low events (under 10 ft) during regional droughts (2001, 2007, 2008, and 2011), but recent evidence from 2019 shows benefits of even moderate low stages (RECOVER 2020). Light penetration improves non-linearly on Lake Okeechobee as stages decline due to the combination of reduced depth, shoreline bathymetry, reduced turbidity, reduced phytoplankton growth, and positive feedbacks to water clarity as SAV coverage expands. Therefore, impacts from high-water events are reduced both in duration and extent when followed by low lake stages.

As a result, two ecological envelopes were developed: one for normal conditions (Normal Envelope, **Figure** G-4), and one for lower stages (Recovery Envelope, **Figure G-5**) following years with high-water impacts. The use of two envelopes allows for variable targets based on antecedent conditions and defines the timing, duration, and frequency of low-water events.

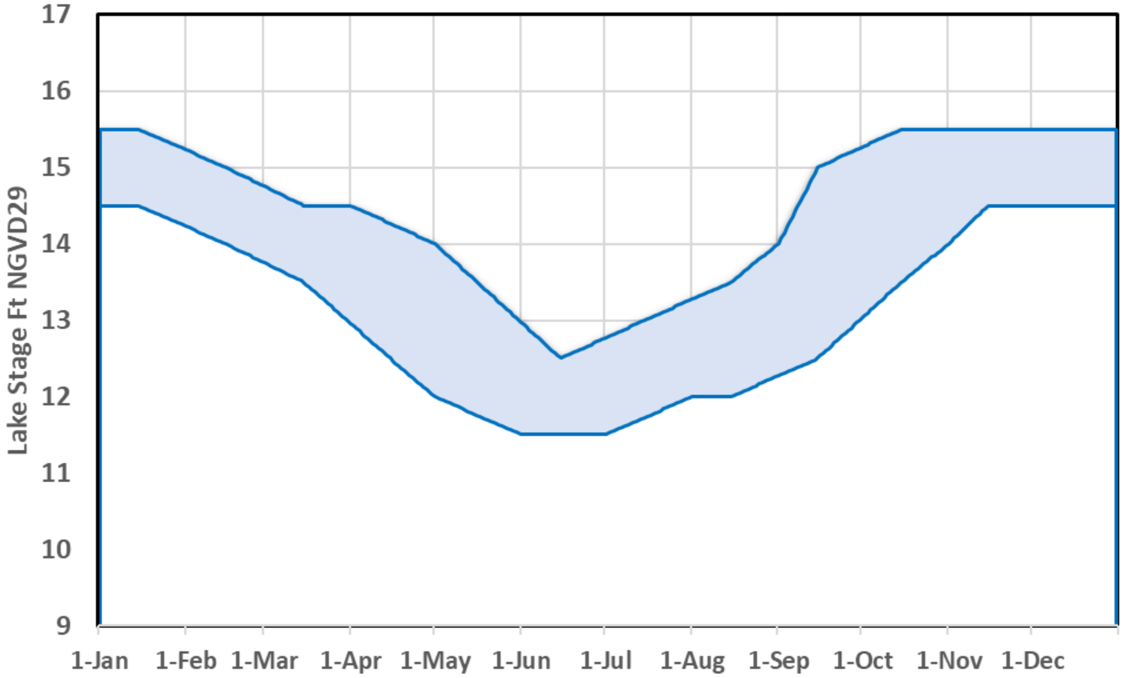


Figure G-4. **Lake Okeechobee stage envelope targets under normal conditions.**

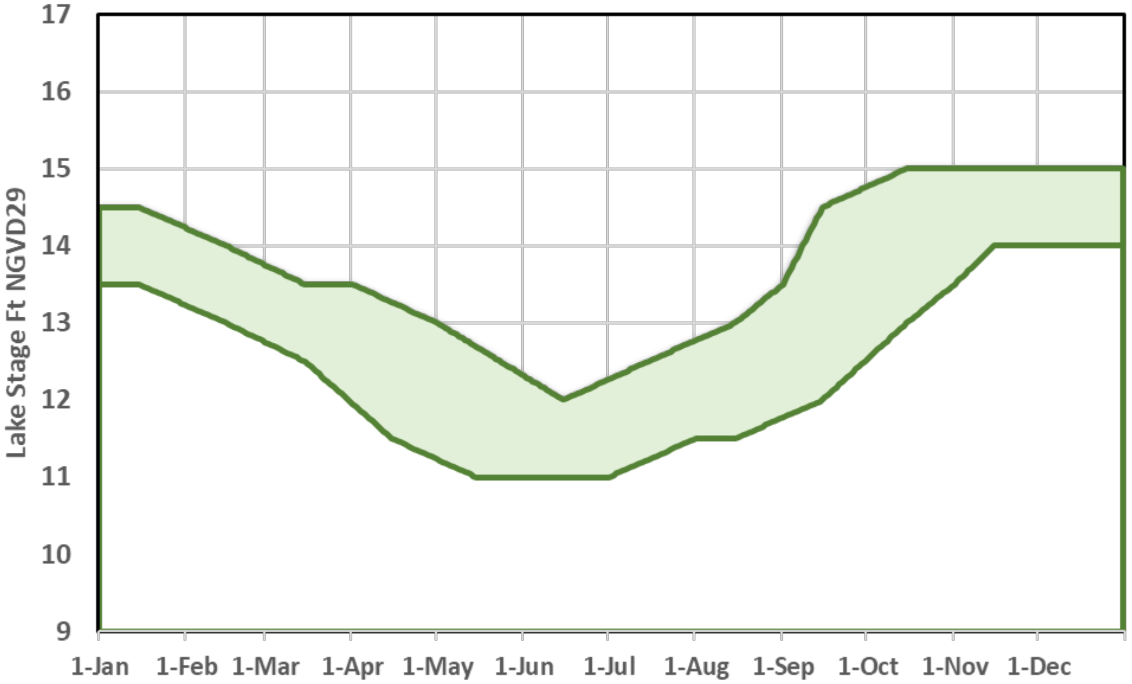


Figure G-5. **Lake Okeechobee stage envelope representing lower stage targets after high-water impacts to lake ecology.**

The Recovery Envelope would be triggered when high-water events are likely to cause substantial stress to SAV or reductions in coverage if not followed by optimal growing conditions the following year. Historically, such events are related to hurricanes, extreme highs (over 17 ft), or high summer stages (Welch et al. 2019). The macroalgae muskgrass (*Chara* spp.) is a good indicator of SAV growing conditions on the lake (Harwell and Sharfstein 2009), dramatically increasing areal coverage when light penetration is high (Havens et al. 2002a, Havens et al. 2002b, Havens et al. 2004). The lowest coverage of this species is related to 30-day minimum summer stages over 13.0 ft (RECOVER 2020). Therefore, a shift from Normal to Recovery envelope (starting Jan 1) would occur when:

- Stages are over 17 ft (5.18 meters [m]) at any time of the year (e.g., 2003, 2004, 2005, 2017)

OR

- The 30-day minimum lake stage (elevations exposed for at least 30 days nonconsecutively) in the June 1 to July 31 window is over 13.0 ft (3.96 m), which represents the years (excluding hurricanes) with the lowest coverage of *Chara* on record (2003, 2010, 2013, 2016)

The thresholds for a shift back to the Normal envelope would similarly be related to SAV coverage (i.e., whether stages were low enough for long enough to allow sufficient germination, growth, and expansion of the populations to survive higher water in the winter and subsequent years). Earlier studies suggest that extreme low stages dry out areas that would otherwise be colonizable by vascular SAV species and that a more diverse community may not establish until 1 to 2 years after extreme low stages. Moderately low stages, however, recently produced rapid expansions of vascular and macroalgae SAV, with peak vascular biomass occurring at elevations that were dried or nearly dried out in the summer of 2019 (RECOVER 2020). The thresholds below approximately correspond to those conditions. However, when heavy rainfall and/or tropical systems impact the lake after low stages, much or all the recovery process can be lost, as was observed in 2017 (low stages followed by rapid ascension rates and then Hurricane Irma) (Welch et al. 2019).

Therefore, a shift from Recovery Envelope to Normal Envelope (starting January 1) would occur when:

- Lake stages are below 12 ft (3.66 m) for 90 days (nonconsecutively) between April 15 and September 15

OR

- Stages are below 11.5 ft (3.51 m) for 60 days (nonconsecutively) between May 1 and August 1
- One of above criteria are met **AND** Lake stages do not exceed 16 ft (4.88 m) before January 1

Evaluation is based on the 52-year (January 1, 1965, to December 31, 2016) hydrograph of lake stages that is simulated by the RSM-BN model. Daily deviations of lake stage from the ecological envelope (Normal or Recovery, whichever has been triggered that year in the model) are determined, and a scoring factor is applied based on distance from the envelope and time of year (RECOVER 2020). This is done separately for stages above and stages below the envelope.

G.3.1.2 PM 1.2 – Lake Okeechobee Extreme High and Low Lake Stage Performance Measure

There is also a wide body of published research on the adverse impacts of extreme high and low water levels on the littoral and near-shore areas of Lake Okeechobee (Havens 2002). Extreme high stage (above

17 ft NGVD29) allows wind-driven waves to directly impact the littoral emergent plant and near-shore submerged plant communities, causing physical uprooting of plants. High stage also permits suspended solids from the mid-lake region (where unconsolidated sediments are thickest), which are transported to the shoreline regions, reducing water clarity and light penetration. This in turn reduces the depth at which SAV growth can occur (James and Havens 2005). High-stage conditions also allow deposition of unconsolidated mud which can cover the natural sand and peat sediment, reducing their ability to sustain healthy and balanced vegetative communities. At extreme high stage, nutrient-rich water from the mid-lake region is transported into the littoral zone where it causes changes in periphyton biomass and taxonomic structure and induces shifts in plant dominance including expansion of cattail and lily. Overall, high lake stages result in extirpation or reduced growth of emergent and submerged plants, adverse impacts to germination of submerged plants, reductions in fish spawning and fish reproductive success, and undesirable shifts among species in the macroinvertebrate community. Detailed research results regarding high stage impacts on the lake's plant and animal communities can be found in Maceina and Soballe (1990), Havens (1997), Havens et al. (1999), and Havens et al. (2001).

Conversely, extreme low stage (below 10 ft NGVD29) can result in desiccation of the entire littoral zone, the shoreline fringing bulrush zone, and nearly all of the lake area that would otherwise support submerged plants. As a consequence, in-lake habitat for reptiles, amphibians, wading birds, snail kites, apple snails, or fish that depend on aquatic plant-dominated regions for successful foraging and recruitment is severely compromised. Extreme low stage also encourages invasive exotic plants, such as torpedograss and melaleuca, to establish in areas of the littoral zone where they did not formerly occur, displacing native vegetation and increasing fire risk. Recovery from the impacts of prolonged low-stage events (below 10 ft mean sea level) is slow, requiring multiple years of appropriate stage regime to recover, as documented for submerged plants by Havens et al. (2004) and for sport fish such as largemouth bass by Havens et al. (2005).

Evaluation is based on the 52-year (January 1, 1965, to December 31, 2016) hydrograph of lake stages that is simulated by the RSM-BN model. For extreme high and low lake stage events, a tally is made of the total number of weeks that the stage is above 17 ft or below 10 ft NGVD29.

G.3.2 Lake Okeechobee Habitat Unit Calculation

The calculation of ecosystem benefits (quantitative scoring) consisted of the following steps: (1) normalizing scores by normalizing PM output to a common scale of 0–1, (2) weighting scores and combining them, and (3) calculating HUs by multiplying the combined PM score by 450,000 acres, as lake stage conditions affect this entire shallow waterbody. While the littoral shelf occupies roughly only 100,000 acres, there is a transitional area between the center limnetic portion of the lake and the littoral shelf, which is often referred to as the "nearshore zone" (also approximately 100,000 acres). Water quality in either offshore region (nearshore or limnetic) can be affected by lake stage, either through changes in things like horizontal transport of nutrients and suspended material (Maceina 1993; Havens and Gawlik 2005) or through wind-induced resuspension or thermal stratification effects on sediment (Havens 1997, James and Havens 2005). In addition, fish distribution offshore can be profoundly affected by lake stage, as the 2006 FFWCC report showed a nearly 200 percent increase in biomass when lake stages dropped (FFWCC 2007), and important limnetic species of game fish like black crappie depend on littoral areas for reproduction. Because lake stage affects all portions of the lake, from the deepwater mud sediments to the highest elevation communities near the levee, SFWMD used the entire 450,000-acre footprint of the lake to calculate HUs.

In Step 1, PM scores were calculated for restoration alternatives and then scaled to a 0 to 1 scale using the normalization process described in this subsection for each PM. In Step 2, PM output scores are weighted by the severity of ecological impact associated with each PM, and, in Step 3, they are multiplied by the area of the lake to generate HUs. The process is described in more detail below. See RECOVER (2020) for more information on scoring prior to normalization.

G.3.2.1 Lake Okeechobee – Normalization, Combining Score and Calculating HUs

Normalization

Raw scores from PMs can be normalized by setting boundary conditions, or best- and worst-case scenarios, to develop a relativized score. The best- and worst-case scenarios for each PM were set according to a recent Lake Okeechobee Regulation Schedule study, which provided scores for a variety of single-objective management strategies that represented realistic boundary conditions for the system based on a 52-year period of record (POR) (Iteration 1 results from the Lake Okeechobee System Operating Manual [LOSOM] development). All the response curves (shown below) convert the annual average of the raw scores for each component of the PM to a standardized scale of 0 to 1, expressed as a percentage. Once a standardized score is calculated, it can be converted to other units of measure, such as HUs, and/or combined with other scores to get a weighted or non-weighted average score for any alternative being evaluated. This method can be used for any modeled POR since it is based on annual averages.

The approach assumes a linear increase in risk of ecological damage between the optimal and most severe conditions, which is the most conservative approach to take until there are data to support a more complex relationship. The equations below would need to be re-calculated if better boundary conditions for any PMs are identified in the future, but it can be used for any modeled POR since it is based on annual averages.

Lake Stage Envelope

Separate response curves were developed for stages above and below the envelope, based on assumptions of best- and worst-case performance for each.

- For scores above the envelope, the response curve is a line between average annual scores of 144.7 (target) and 816.3 (worst case). Raw scores can be converted using the following equation:

  Standardized score (%) = raw score * -0.1489 + 121.550
  (**Figure G-6a**)

- For deviation of lake stage below the envelope, the response curve is a line between 103.4 (target) and 464.6 (worst case). Raw scores can be converted using the following equation:

  Standardized score (%) = raw score * -0.2769 +128.635
  (**Figure G-6b**)

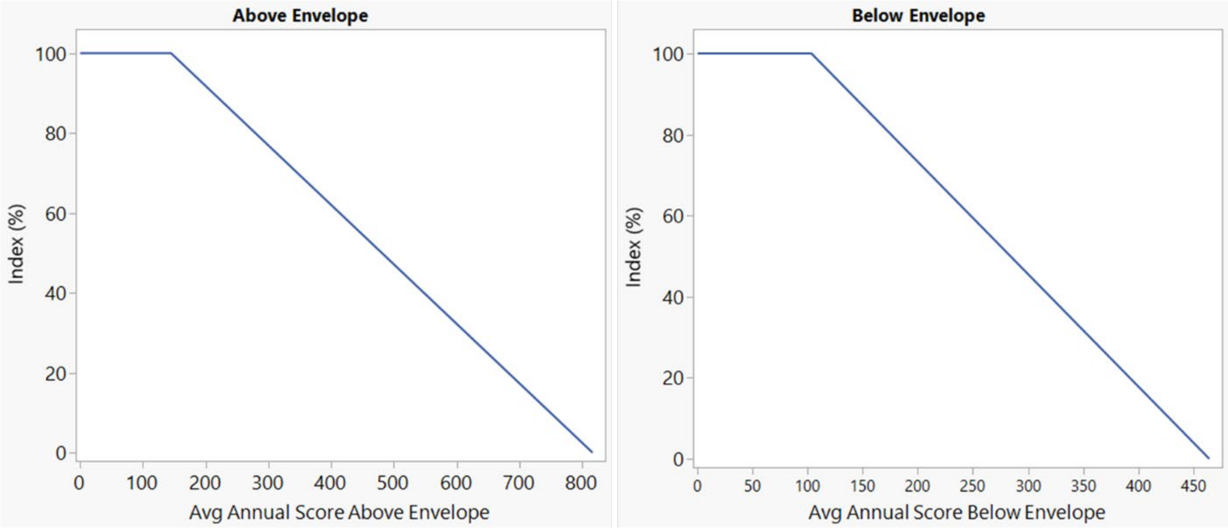


Figure G-6. **Response curves for converting raw average annual scores to normalized scores for above (a) and below (b) lake stage envelope performance measures.**

High and Low Lake Stage

The same approach is used for high and low extreme stage PMs but based on percent duration (number of days in POR) above or below extreme stages.

- For time above 17 ft NGVD: The target is no exceedances, or 0 percent duration, and the worst-case scenario was 6 percent duration. The response curve is a line between 0 percent (target) and 6 percent (worst case). Raw scores can be converted using the following equation:

  Standardized score (%) = raw score * -16.67 +100
  (**Figure G-7a**)

- Time below 10 ft NGVD: The target is no exceedances, or 0 percent duration, and the worst-case scenario was 9 percent duration. The response curve is a line between 0 percent (target) and 9 percent (worst case). Raw scores can be converted using the following equation:

  Standardized score (%) = raw score * -11.11 +100
  (**Figure G-7b**)

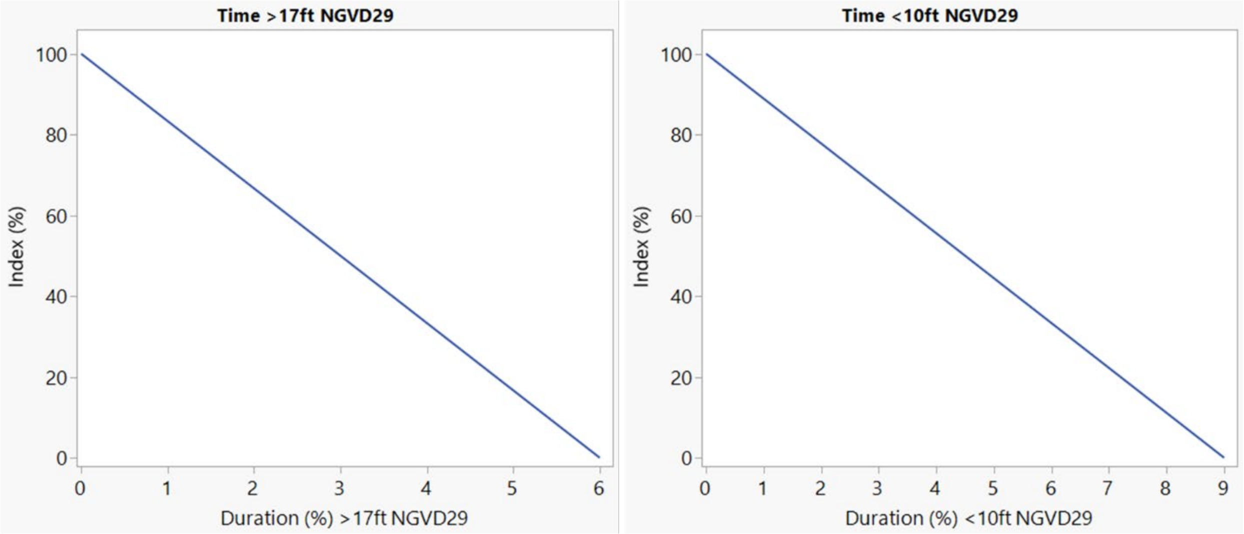


Figure G-7. Response curves for converting percent duration above 17 ft NGVD (a) and below 10 ft NGVD (b) over the period of record to normalized scores.

Weighting of Normalized Performance Output

The four PMs are combined prior to calculating HUs and weighted according to risk.

- High stage (above envelope and time above 17 ft NGVD) is applied a weight of 66.7 percent.
- Low stage (below envelope and time below 10 ft NGVD) is applied a weight of 33.3 percent.

The weighting formula for the Final Combined Score (%) =

[(PM Above Envelope +PM >17 ft) *0.667 + (PM Below Envelope +PM <10 ft) *0.333]/2

This approach is consistent with past research showing high stages can have potentially more damaging impacts to lake ecology than low stages, in that the latter can be beneficial if the return frequency is low enough. This method also accounts for the fact that raising lake stages to avoid low-stage impacts would be counterproductive in terms of lake health, because even the wettest possible schedules still have occasional droughts that overwhelm the system. The best long-term solution is to provide sufficient watershed storage to offset both high and low stages. Assigning more weight to high lake stage PMs effectively assigns better scores to alternatives that reduce both high and low stages vs alternatives that offset high stage scores with improvement in low stage scores (i.e., very wet alternatives).

Calculating Habitat Unit

The combined, weighted scores for each alternative are then multiped by 450,000 ac, the approximate size of Lake Okeechobee. **Figure G-8** shows the stage duration curves for the final array of alternatives. The total acres of lift for any alternative are equivalent to the difference between the FWO score and the alternative score.

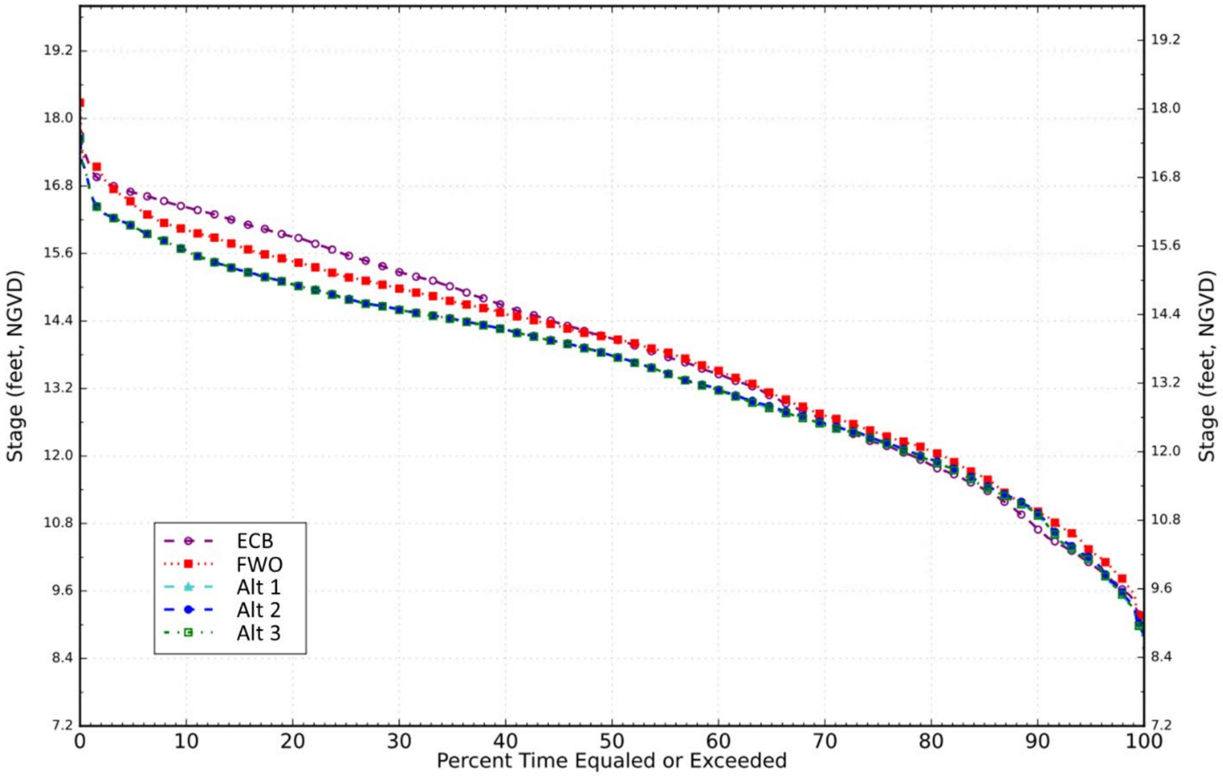


Figure G-8. **Lake Okeechobee stage duration curves for the final array of alternatives.**

G.3.2.2 Lake Okeechobee Stage PM HUs

Lake Okeechobee Stage Envelope and Extreme Stage PM

Outputs were normalized using the approach outlined above, creating individual scores of 0 to 100 percent for each metric (**Figure G-9)**. Those normalized scores for above and below the envelope, and above and below 17 ft and 10 ft NGVD29 were then weighted as described above, which are shown for the final array of alternatives in

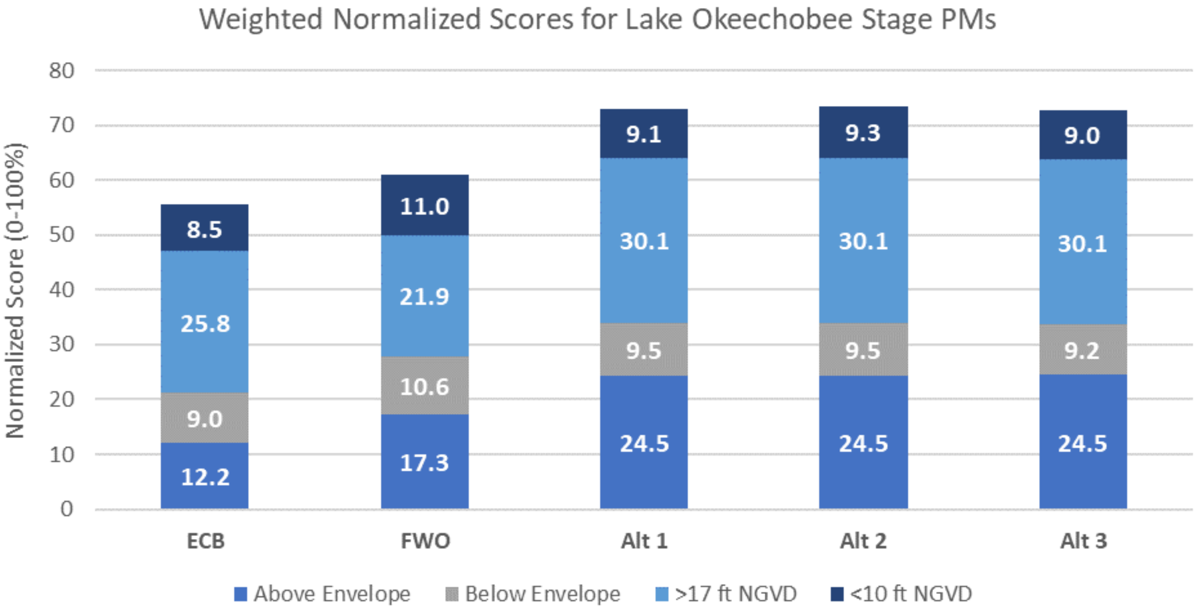


Figure G-10.

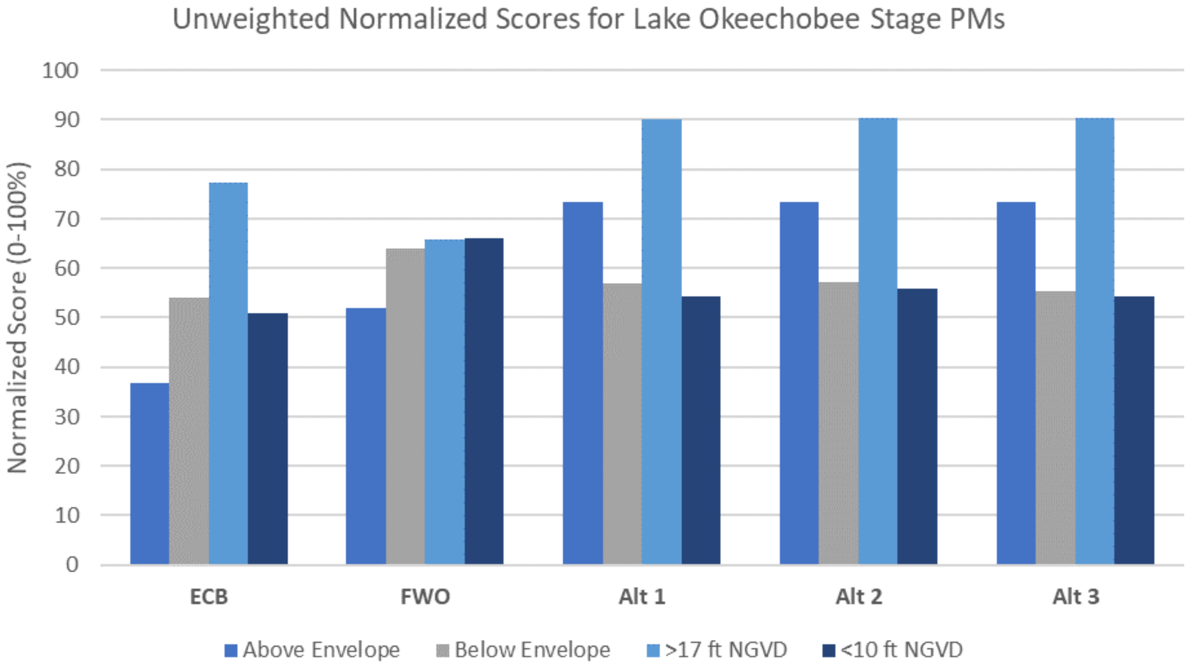


Figure G-9. Normalized scores for Lake Okeechobee stage PMs for the final array of alternatives.

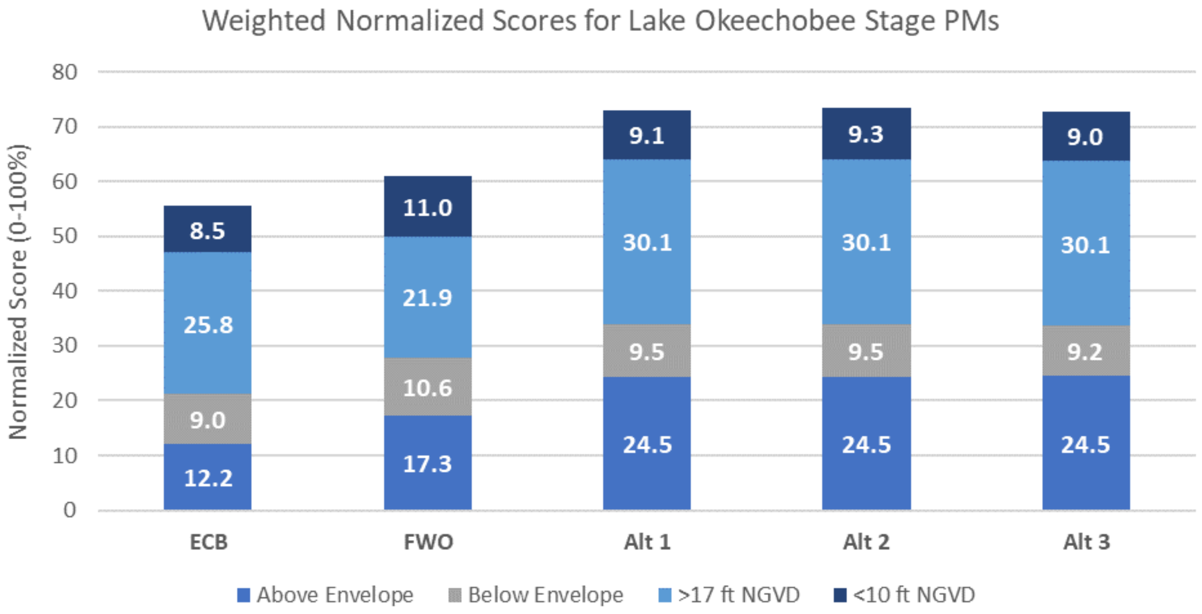


Figure G-10. Normalized and weighted scores for Lake Okeechobee stage PMs for the final array of alternatives.

HU Calculations for Alternatives

The normalized Lake Stage PM scores were weighted (**Figure G-11**) by the approach outlined above and combined for a finalized PM score to calculate HUs (**Table G-3**).

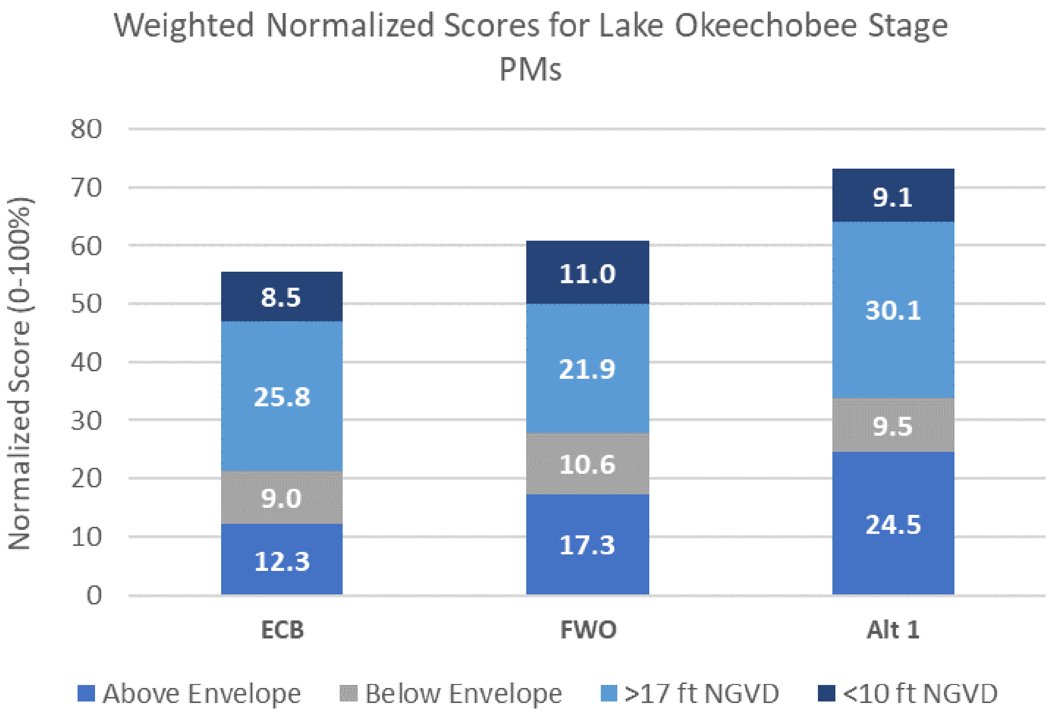


Figure G-11. Weighted and normalized scores for Lake Okeechobee stage PMs output for the Recommended Plan.

Table G-3. Lake Okeechobee Stage PM Scores, Weighted Combined Scores, and Habitat Units for the Final Array of Alternatives.[1]

Alternative	Above Envelope PM	Below Envelope PM	Extreme High PM	Extreme Low PM	Weighted Combined Score (0-100)	Habitat Units (0-450k)	Potential Lift (HUs)
ECB	569.8 (36.8)	269.3 (54.1)	1.36% (77.3)	4.41% (51.0)	55.6	250,073	N/A
FWO	467.3 (52.0)	234.0 (63.9)	2.05% (65.8)	3.05% (66.1)	61.0	274,335	N/A
Alternative 1	323.5 (73.4)	258.9 (57.0)	0.59% (90.2)	4.11% (54.3)	73.1	328,902	54,568
Alternative 2	323.7 (73.4)	258.1 (57.2)	0.58% (90.3)	3.98% (55.8)	73.4	330,369	56,034
Alternative 3	323.4 (73.5)	265.1 (55.3)	0.58% (90.3)	4.12% (54.2)	72.8	327,822	53,487

1. Lower scores are better for the PMs, while higher scores are better for the Weighted Combined Scores and Habitat Units. Normalized scores for PMs are in parentheses.

G.3.3 Lake Okeechobee Alternative Performance

Table G-4 shows the Lake Okeechobee HUs for each of the alternatives. Alternative 2 provides the greatest HU lift of 56,034 acres, followed by Alternative 1 with 54,568 acres, and then Alternative 3 with 53,487 acres.

Table G-4. Summary Lake Okeechobee Habitat Unit Trajectory by Alternative.

Alternative	ECB Lake O HUs (2033)	FWP Lake O HUs (2035)	FWP Lake O HUs (2038)	FWP Lake O HUs (2043)	FWP Lake O HUs (2058)	FWP Lake O HUs (2083)	Average Annual Lake O HU Lift (from ECB)
FWO	250,073	251,043	252,499	254,925	262,204	274,335	485
Alternative 1	250,073	269,780	289,488	297,370	328,902	328,902	1,577
Alternative 2	250,073	270,147	290,221	298,251	330,369	330,369	1,606
Alternative 3	250,073	269,510	288,948	296,722	327,822	327,822	1,555

The Lake Okeechobee average annual HU (AAHU) lifts were calculated as the difference between the Future With Project (FWP) and FWO conditions over the period of analysis (through year 2083). For the FWO condition, a straight trajectory between existing and FWO HUs was assumed to establish HU totals for each site and year.

With project HU trajectory was modeled to reflect the timeline of expected restoration effects. Lake Okeechobee HUs for each alternative are assumed to reach 25 percent potential 2 years following construction completion, 50 percent potential 5 years following construction completion, 60 percent potential 10 years following construction completion, and 100 percent potential 25 years following construction completion. At that point, the full potential of HUs will be realized for the remainder of the period of analysis. The resulting average annual HU lift (from ECB or FWO) is also displayed in **Table G-4**.

The AAHUs for Lake Okeechobee will be combined with the Northern Estuaries HUs for the storage cost-effectiveness and incremental cost analysis (CE/ICA). The CE/ICA is evaluated in **Section G.5**.

G.3.4 Lake Okeechobee Recommended Plan Performance

This section outlines the HU analysis for the Recommended Plan (Alternative 1).

G.3.4.1 Lake Okeechobee Recommended Plan Stage Performance Measures and HUs

The Lake Okeechobee Stage PM output is shown in **Table G-5** for the Recommended Plan. The scores for the envelope (above and below) and time exceeding extreme stages (above 17 ft and under 10 ft NGVD29) are combined and normalized based on their performance relative to theoretical best- and worst-case scenarios. The above envelope and time above 17 ft scores are weighted by 0.67, while the time below the envelope and time under 10 ft are weighted by 0.33. The combined, weighted score is multiplied by the 450,000-acre lake size to calculate HUs. See **Section G.3.2.1** for more details on the normalization and weighting methodology.

Table G-5. Summary Lake Okeechobee PM and HUs for the Recommended Plan.

Alternative	Above Envelope PM	Below Envelope PM	Extreme High PM	Extreme Low PM	Weighted Combined Score (0-100)	Habitat Units (0-450k)	Potential Lift (HUs)
ECB	569.8 (36.8)	269.3 (54.1)	1.36% (77.3)	4.41% (51.0)	55.6	250,073	N/A
FWO	467.3 (52.0)	234.0 (63.9)	2.05% (65.8)	3.05% (66.1)	61.0	274,335	N/A
Alternative 1	323.5 (73.4)	258.9 (57.0)	0.59% (90.2)	4.11% (54.3)	73.1	328,902	54,568

G.3.4.2 Lake Okeechobee Recommended Plan Performance

Table G-6 shows the trajectory of Lake Okeechobee HUs for the recommended plan from 2033 through 2083, as well as the AAHU lift. The Lake Okeechobee AAHU lift for the Recommended Plan is 1,577 from ECB, or 1,091 from FWO.

Table G-6. Summary Lake Okeechobee Recommended Plan Habitat Unit Trajectory.

Alternative	ECB Lake O HUs (2033)	FWP Lake O HUs (2035)	FWP Lake O HUs (2038)	FWP Lake O HUs (2043)	FWP Lake O HUs (2058)	FWP Lake O HUs (2083)	Average Annual Lake OHU Lift from ECB
FWO	250,073	251,043	252,499	254,925	262,204	274,335	485
Alternative 1	250,073	269,780	289,488	297,370	328,902	328,902	1,577

G.4 Northern Estuaries Benefit Calculation

The primary areas evaluated in the Northern Estuaries are Caloosahatchee Estuary (**Figure G-2**) and St. Lucie Estuary (**Figure G-3**). These two estuaries connect directly to Lake Okeechobee, as well as expansive watersheds much larger than their historical condition.

G.4.1 Northern Estuaries Performance Measures

PMs within the Northern Estuaries were used to evaluate benefit for oyster habitat based on target flows over water control structures. Within the Caloosahatchee Estuary, targets were based on freshwater flows at the S-79 structure (**Figure G-2** and **Figure G-12**). Within the St. Lucie Estuary, targets were based on freshwater flows at the S-80, S-48, S-49, and Gordy Road structures (**Figure G-3** and **Figure G-12**).

The RSM-BN outputs for the Northern Estuaries are based on the RECOVER PM for Northern Estuaries Salinity Envelope (RECOVER 2020). Each estuary has 14-day flow criteria derived from the Curvilinear, Hydrodynamic 3-Dimensional (CH3D) Model, which models estuary-wide salinities that are optimal, stressful, or damaging to key ecological indicator species. For the St. Lucie Estuary (SLE), this includes shoal grass (*Halodule wrightii*, a mesohaline seagrass), and the Eastern oyster (*Crassostrea virginica*, a mesohaline bivalve); and for the Caloosahatchee Estuary (CRE), it includes these species in addition to tape grass (*Vallisneria americana*, a freshwater and oligohaline submerged aquatic vegetation). The below sections describe the CRE and SLE-specific flow metrics for use in alternatives evaluation, as well as HU methodology used in benefits analysis.

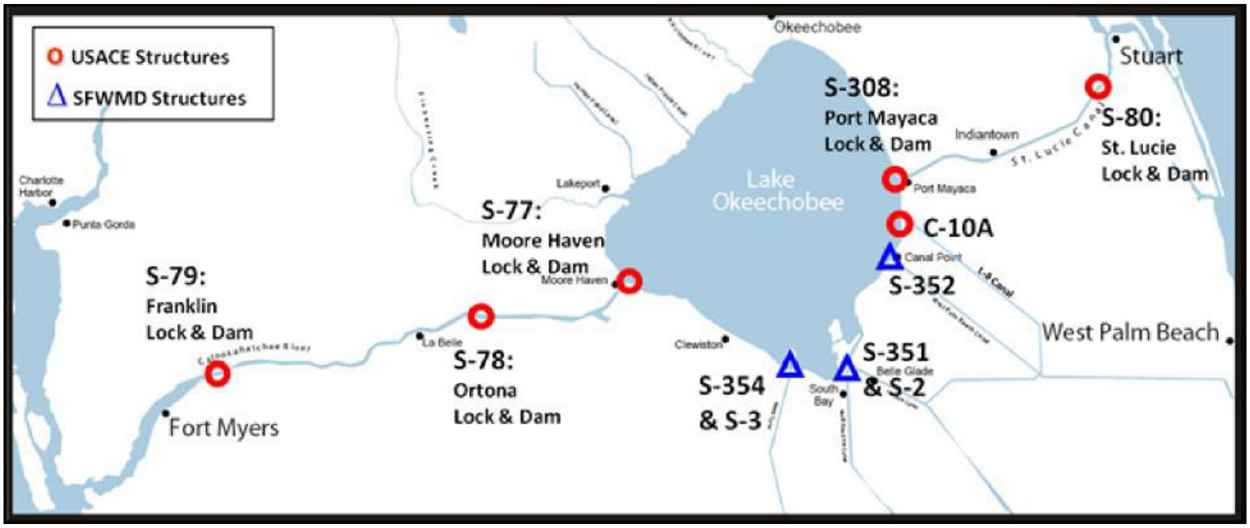


Figure G-12. Key structures of Lake Okeechobee and the Northern Estuaries.

G.4.1.1 PM 3 - Caloosahatchee River Estuary Salinity Envelope Performance Measure

The PMs used for the CRE are from RECOVER (2020) (**Table G-7**).

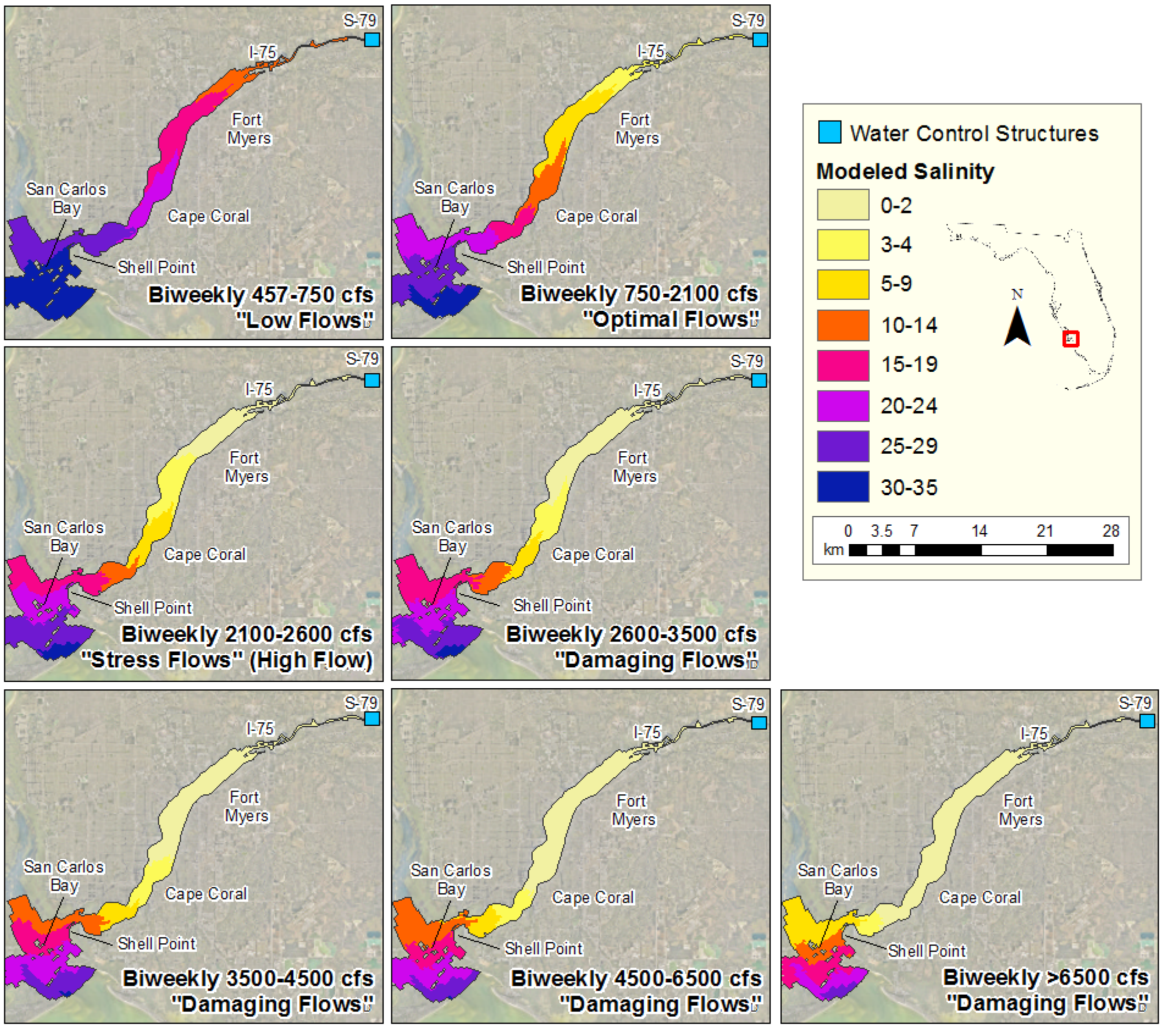
Table G-7. Caloosahatchee Estuary Performance Metrics, from RECOVER (2020).[1/]

Performance Metrics based on simulated flows at S-79 into the Caloosahatchee River and Estuary
Low Flow - # of 14-day periods <750 cfs
Optimal Flow - # of 14-day periods >=750 cfs and <2,100 cfs
High Flow (Basin Runoff) - # of 14-day periods >= 2,100 cfs and <2,600 cfs
High Flow (LOK Regulatory[2/]) - # of 14-day periods >= 2,100 cfs and <2,600 cfs
Damaging Flow (Basin Runoff) - # of 14-day periods >= 2,600 cfs
Damaging Flow (LOK Regulatory) - # of 14-day periods >= 2,600 cfs
Damaging Flow (Total Flows[3/]) - # of 14-day periods >= 2600 and <= 4500 cfs
Damaging Flow (Total Flows) - # of 14-day periods >= 4500 and <= 6500 cfs

Performance Metrics based on simulated flows at S-79 into the Caloosahatchee River and Estuary
Damaging Flow (Total Flows) - # of 14-day periods >= 6500 cfs

1/ Simulated 14-day moving average flow events that fall within each of the flow ranges below are classified based on resulting salinities and oyster and submerged aquatic vegetation salinity tolerances.
2/ LOK Regulatory = Lake Okeechobee Regulatory Releases
3/ Total flows from both LOK Regulatory and basin runoff

The CRE PMs (**Table G-7**) were derived from modeled salinity using the CH3D model (Sheng 1986) and evaluated by RECOVER scientists to establish categories (e.g., optimal, stress, damaging flow) according to impact to oyster and SAV species (**Figure G-13**).



Note: Average salinity is based on 14-day moving average flows in each bin.

Figure G-13. Modeled salinity of RECOVER (2020) performance measures for the CRE.

With RECOVER (2020) "Low Flows," average salinity is between 10 and 14, outside of the optimal range for tape grass (*Vallisneria americana*) whose distribution can be found upstream of Fort Myers to the tidal boundary at S-79 (**Figure G-13**). "Optimal Flows" provide an estuarine gradient throughout the CRE to support tape grass in the upper estuary, and oyster (*Crassostrea virginica*) and SAV in the middle and lower estuary San Carlos Bay. With “Stress Flows,” there is declining salinity around Cape Coral, near the upstream extent of oyster reef in the CRE; the stress category is conservative, to minimize impact to oysters further downstream. Finally, while RECOVER (2020) defines “Damaging Flows” as anything above 2,600 cubic feet per second (cfs) 14-day moving average (ma), and is similarly conservative to minimize low salinity impacts, additional bins above this threshold were modeled to demonstrate impact to the lower estuary and San Carlos Bay. 14-day ma flows of 3,500 to 4,500 cfs result in modeled salinity 15 parts per thousand (ppt) or less in the whole estuary; 14-day ma flows of 4,500 to 7,500 cfs results in salinity 10 ppt or less throughout; and 14-day ma flows over 6,500 cfs results in the whole CRE as having extremely low salinities and being unable to support oysters and SAV. Additional impacts are felt in the San Carlos Bay.

G.4.1.2 PM 4 - St. Lucie Estuary Salinity Envelope Performance Measure

The PMs used for the SLE are from RECOVER (2020) (**Table G-8**).

Table G-8. St. Lucie Estuary Performance Metrics, from RECOVER (2020).[1/]

Performance Metrics based on simulated flows into the St. Lucie River and Estuary
Low Flow - # of 14-day periods <150 cfs
Optimal Flow - # of 14-day periods >=150 cfs and <1,400 cfs
High Flow (Basin Runoff) - # of 14-day periods >= 1,400 cfs and <1,700 cfs
High Flow (LOK Regulatory[2/]) - # of 14-day periods >= 1,400 cfs and <1,700 cfs
Damaging Flow (Basin Runoff) - # of 14-day periods >= 1,700 cfs
Damaging Flow (LOK Regulatory) - # of 14-day periods >= 1,700 cfs
Damaging Flow (Total Flows[3/]) - # of 14-day periods >= 1,700 and <= 4000 cfs
Damaging Flow (Total Flows) - # of 14-day periods >= 1,700

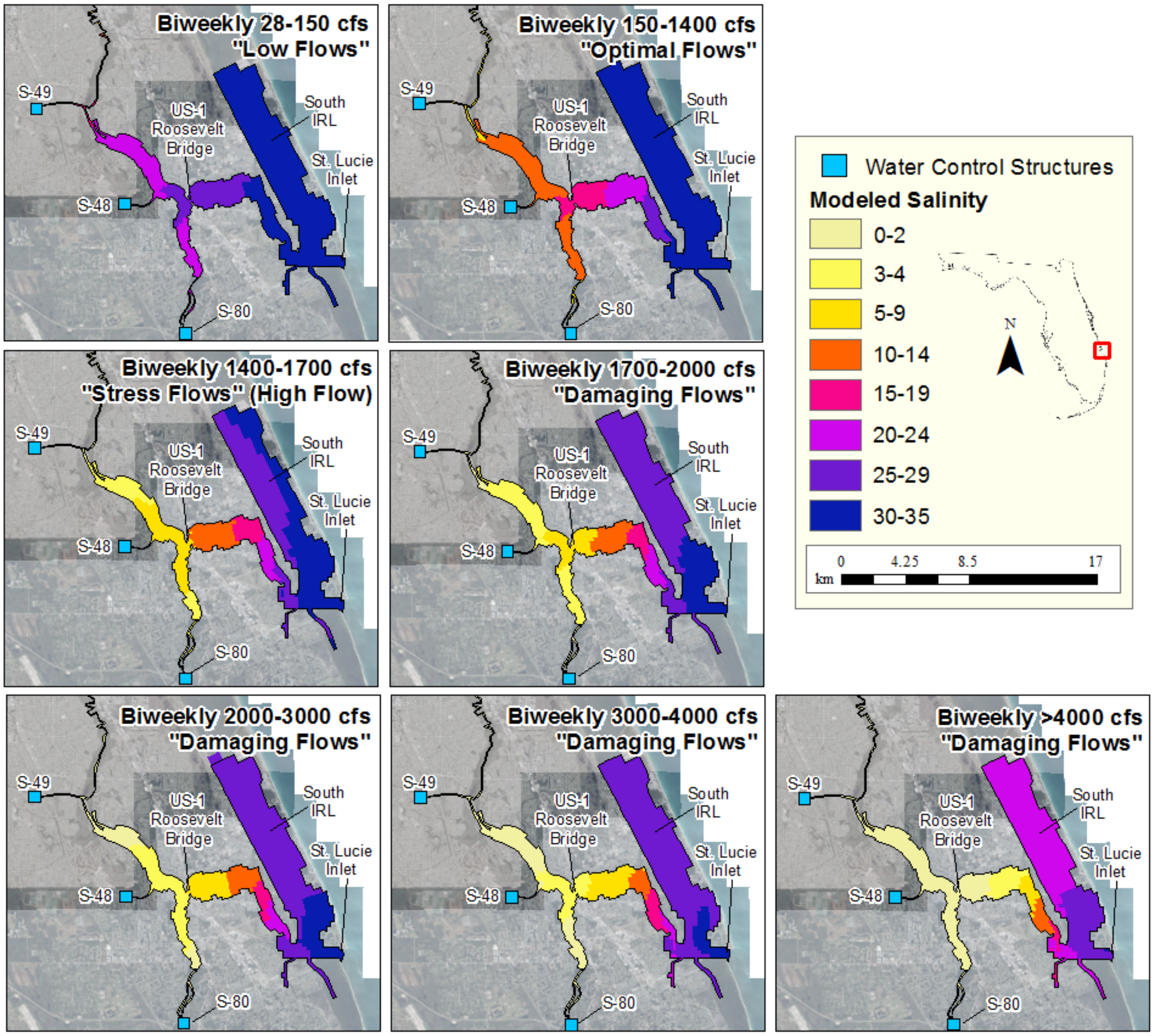
[1/] Simulated 14-day ma flow events that fall within each of the flow ranges below are classified based on resulting salinities and oyster and submerged aquatic vegetation salinity tolerances.

[2/] LOK Regulatory = Lake Okeechobee Regulatory Releases

[3/] Total flows from both LOK Regulatory and basin runoff

The SLE PMs (**Table G-8**) were derived from modeled salinity using the CH3D model (Sheng 1986), and evaluated by RECOVER scientists to establish categories (e.g., optimal, stress, damaging flow) according to impacts to oyster and SAV species (**Figure G-14**).

With RECOVER (2020) “Low Flows” in the SLE, salinities throughout the estuary are suitable for oysters and SAV, but salinities increase to 10 to 14 ppt upstream in the St. Lucie River and may have a negative impact on nursery habitat for communities of juvenile fish which often congregate in the oligohaline zone in the river (Stephens et al. 2022). “Optimal Flows” provide suitable salinities for these species in the river and estuary, without any impact to marine salinities in the southern Indian River Lagoon (IRL) near the St. Lucie Inlet (**Figure G-14**). As flows increase, salinity declines to less than 10 ppt in the north and south forks of the SLE. Historically, oyster reefs in the forks are less dense and exist in higher ratios of dead-to-live oysters per unit area than in the middle estuary; the RECOVER (2020) “Stress Flow” category is similarly conservative to protect the middle estuary from experiencing salinities under 10 ppt. With 14-day ma flows between 1,700 and 20,00 cfs (RECOVER [2020]). With “Damaging Flows,” the low-salinity wedge pushes further downstream into the middle estuary. 14-day ma flows over 4,000 cfs result in fresh-to-extreme-low salinities throughout the forks and portions of the middle estuary, and salinities below 10 ppt past the A1A bridge.



Note: Average salinity is based on 14-day ma flows in each bin.

Figure G-14. Modeled salinity of RECOVER (2020) performance measures for the SLE.

G.4.1.3 Northern Estuaries – Normalization, Combining Score and Calculating HUs

The calculation of ecosystem benefits consisted of the following steps: 1) Normalize Scores—normalizing each of the Performance Metrics to a common scale for (0 to 100); 2) Combine Scores and Calculate Northern Estuaries HUs—combine PMs into aggregate scores and multiply by the available habitat (acres) of oyster reef in each estuary; and 3) Compare HUs—Aggregate Northern Estuaries HUs with other resource area HUs (in the case of LOCAR, Lake Okeechobee) and compare across project alternatives, ECB, and FWO.

Normalization

RSM-BN outputs for the Salinity Envelope PM (RECOVER 2020) were normalized by setting boundary conditions, or best- and worst-case scenarios, to develop a relativized score. The best- and worst-case scenarios for each PM were set according to a recent Lake Okeechobee Regulation Schedule study, which provided scores for a variety of single-objective management strategies that represented realistic boundary conditions for the system based on a 52-year period of simulation (Iteration 1 results from LOSOM development).

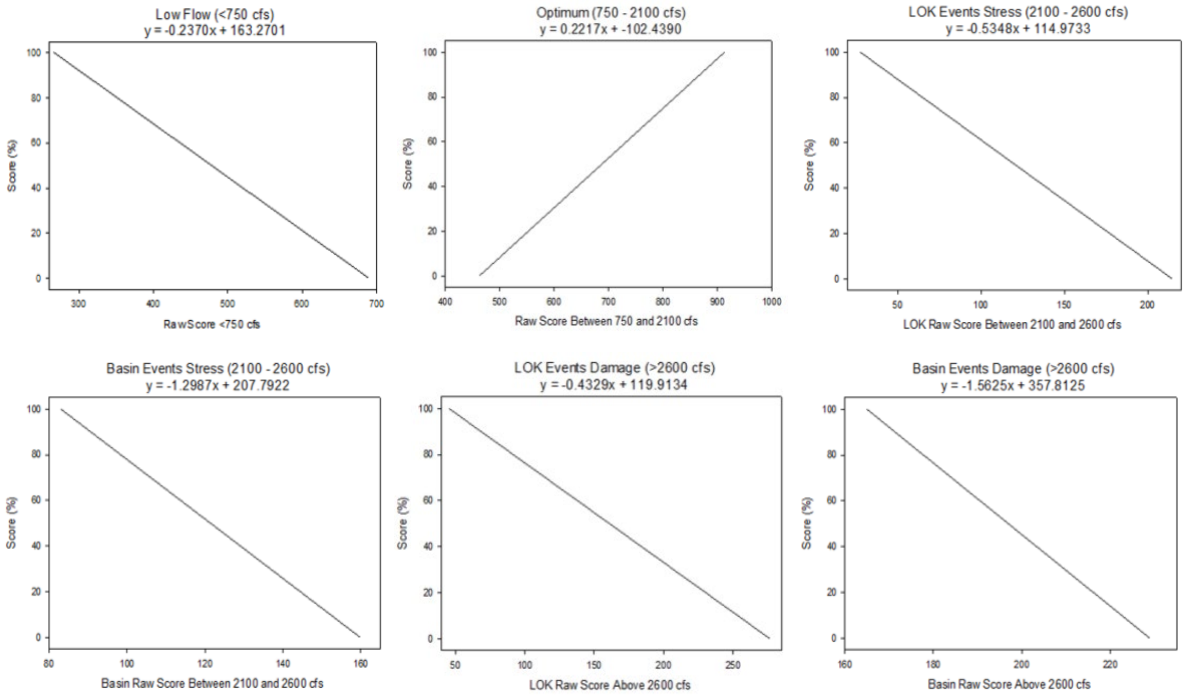
Table G-9. Salinity Envelope Performance Measure (RECOVER 2020) Modeling Results from LOSOM Iteration 1 Single-objective Management Scenarios Compared to ECB and No Action Alternative (2025).

Salinity Envelope Performance Metric	ECB	2025	ECRE	ELSE	ESFL	ABNE	LOK	WRDS	WRDC	WAS	REC	NAV
Caloosahatchee River Estuary LOSOM Iteration 1 Results												
Low Flows (Biweekly <750 cfs)	652	560	350	267	689	286	654	465	521	636	543	626
Optimal Flows (Biweekly 750-2100 cfs)	462	606	913	728	607	901	498	581	758	483	575	490
Stress (High) Flows triggered by LOK* (Biweekly 2100-2600 cfs)	147	122	126	83	157	133	114	98	160	95	124	105
Stress (High) Flows triggered by Basin Runoff (Biweekly 2100-2600 cfs)	201	170	86	215	28	104	157	186	71	149	116	146
Damaging Flows triggered by LOK* (Biweekly >2600 cfs)	229	175	172	178	165	194	172	177	189	188	184	191
Damaging Flows triggered by Basin Runoff (Biweekly >2600 cfs)	217	169	59	277	74	74	194	273	46	225	256	213
St. Lucie Estuary LOSOM Iteration 1 Results												
Low Flows (Biweekly <150 cfs)	104	105	84	176	126	73	131	173	128	152	167	151
Optimal Flows (Biweekly 150-1400 cfs)	840	828	864	937	886	903	819	940	697	874	935	882
Stress (High) Flows triggered by LOK* (Biweekly 1400-1700 cfs)	211	170	142	325	245	195	154	328	115	213	323	249
Stress (High) Flows triggered by Basin Runoff (Biweekly 1400-1700 cfs)	145	180	175	0	70	144	205	0	221	115	1	73
Damaging Flows triggered by LOK* (Biweekly >1700 cfs)	449	421	401	465	436	427	414	467	409	439	468	452
Damaging Flows triggered by Basin Runoff (Biweekly >1700 cfs)	137	166	178	4	92	103	190	0	255	99	8	76

Note: Worst and best scores were taken as boundary conditions for performance metric score normalization.

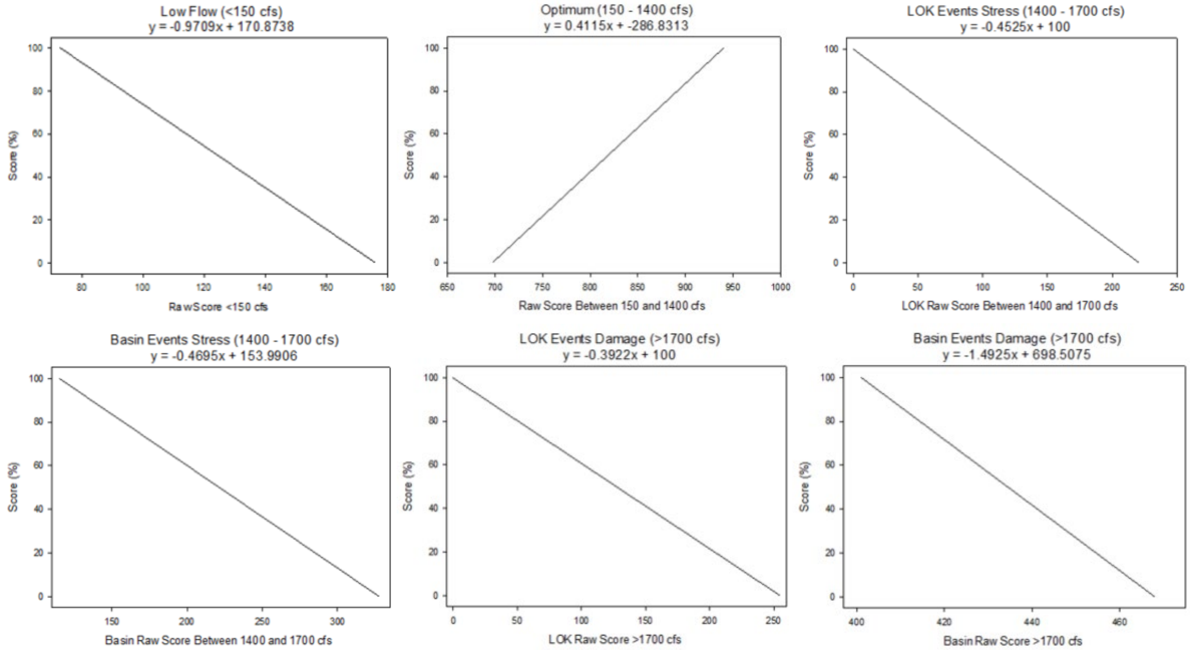
The response curves (**Figure G-15** and **Figure G-16**) convert the total number of 14-day ma flow events for each Performance Metric from the RECOVER (2020) Salinity Envelope PM ("raw scores") (**Attachments G-1** and **G-2**) to a standardized scale of 0 to 100, from worst- to best-case according to the boundary conditions. Once this standardized score is calculated, it can be converted to other units of measure, such as HUs, and/or combined with other scores to get a weighted or non-weighted average score for any alternative being evaluated. For this study, acreages of oysters were used to calculate HUs. Oysters were mapped in 2019 in the CRE and SLE, totaling 980 and 434 acres of reef, respectively. The 2019 maps differentiate between mostly dead or mostly live oysters within a reef or clump, but for the purpose of HU calculations, all available shell material was treated as habitat.

The approach assumes a linear increase in risk of ecological damage between the optimal and most severe conditions, which is the most conservative approach to take until there are data to support a more complex relationship.



Note: Worst- and base-case boundary conditions (x-axis) from LOSOM Iteration 1 single-objective management scenarios; and normalization score (%) 0-100.

Figure G-15. Response curves of the CRE salinity envelope performance metrics (RECOVER 2020).



Note: Worst- and base-case boundary conditions (x-axis) from LOSOM Iteration 1 single-objective management scenarios; and normalization score (%) 0-100.

Figure G-16. Response curves of the SLE salinity envelope performance metrics (RECOVER 2020).

Caloosahatchee Estuary Habitat Unit Calculations

Separate response curves were developed for each of the CRE Performance Metrics (RECOVER 2020) based on assumptions of worst- and best-case possible performance for each (**Section G.4.1.3.1**; **Figure G-15**). To normalize the scores, the response curves were applied to the model outputs ("raw scores") for LOCAR.

- For CRE Low Flows (14-day ma flows under 750 cfs), the response curve is a line between the number of events from the LOSOM Iteration 1 period of simulation: 267 (target) and 689 (worst case). Raw scores are the model outputs for LOCAR for each alternative. Normalized scores can be converted using the following equation (y = mx+b):

  Normalized Score (%) = (-0.237*Raw Score) + 163.27

- For CRE Optimal Flows (14-day ma flows between 750 and 2,100 cfs), the response curve is a line between the number of events from the LOSOM Iteration 1 period of simulation: 913 (target) and 462 (worst case). Raw scores are the model outputs for LOCAR for each alternative. Normalized scores can be converted using the following equation (y = mx+b):

  Normalized Score (%) = (0.2217*Raw Score) + (-102.44)

- For CRE Stress (High) Flows (14-day ma flows between 2,100 and 2,600 cfs) triggered by Lake Okeechobee Regulatory Releases, the response curve is a line between the number of events from the LOSOM Iteration 1 period of simulation: 28 (target) and 215 (worst case). Raw scores are the model outputs for LOCAR for each alternative. Normalized scores can be converted using the following equation (y = mx+b):

  Normalized Score (%) = (-0.535*Raw Score) + 114.97

- For CRE Stress (High) Flows (14-day ma flows between 2,100 and 2,600 cfs) triggered by basin runoff, the response curve is a line between the number of events from the LOSOM Iteration 1 period of simulation: 83 (target) and 160 (worst case). Raw scores are the model outputs for LOCAR for each alternative. Normalized scores can be converted using the following equation (y = mx+b):

  Normalized Score (%) = (-1.299*Raw Score) + 207.79

- For CRE Damaging Flows (14-day ma flows above 2,600 cfs) triggered by Lake Okeechobee Regulatory Releases, the response curve is a line between the number of events from the LOSOM Iteration 1 period of simulation: 46 (target) and 277 (worst case). Raw scores are the model outputs for LOCAR for each alternative. Normalized scores can be converted using the following equation (y = mx+b):

  Normalized Score (%) = (-0.433*Raw Score) + 119.91

- For CRE Damaging Flows (14-day ma flows above 2600 cfs) triggered by basin runoff, the response curve is a line between the number of events from the LOSOM Iteration 1 period of simulation: 165 (target) and 229 (worst case). Raw scores are the model outputs for LOCAR for each alternative. Normalized scores can be converted using the following equation (y = mx+b):

  Normalized Score (%) = (-1.563*Raw Score) + 357.81

St. Lucie Estuary Habitat Unit Calculations

Separate response curves were developed for each of the SLE Performance Metrics (RECOVER 2020) based on assumptions of best- and worst-case possible performance for each (**Section G.4.1.3.1**; **Figure G-16**). To normalize the scores, the response curves were applied to the model outputs ("raw scores") for LOCAR.

- For SLE Low Flows (14-day ma flows less than 150 cfs), the response curve is a line between the number of events from the LOSOM Iteration 1 period of simulation: 73 (target) and 176 (worst case). Raw scores are the model outputs for LOCAR for each alternative. Normalized scores can be converted using the following equation (y = mx+b):

  Normalized Score (%) = (-0.971*Raw Score) + 170.87

- For SLE Optimal Flows (14-day ma flows between 150 and 1,400 cfs), the response curve is a line between the number of events from the LOSOM Iteration 1 period of simulation: 940 (target) and 697 (worst case). Raw scores are the model outputs for LOCAR for each alternative. Normalized scores can be converted using the following equation (y = mx+b):

  Normalized Score (%) = (0.412*Raw Score) + (-286.83)

- For SLE Stress (High) Flows (14-day ma flows between 1,400 and 1,700 cfs) triggered by Lake Okeechobee Regulatory Releases, the response curve is a line between the number of events from the LOSOM Iteration 1 period of simulation: 0 (target) and 221 (worst case). Raw scores are the model outputs for LOCAR for each alternative. Normalized scores can be converted using the following equation (y = mx+b):

  Normalized Score (%) = (-0.453*Raw Score) + 100

- For SLE Stress (High) Flows (14-day ma flows between 1,400 and 1,700 cfs) triggered by basin runoff, the response curve is a line between the number of events from the LOSOM Iteration 1 period of simulation: 115 (target) and 328 (worst case). Raw scores are the model outputs for LOCAR for each alternative. Normalized scores can be converted using the following equation (y = mx+b):

  Normalized Score (%) = (-0.469*Raw Score) + 153.99

- For SLE Damaging Flows (14-day ma flows above 1,700 cfs) triggered by Lake Okeechobee Regulatory Releases, the response curve is a line between the number of events from the LOSOM Iteration 1 period of simulation: 0 (target) and 255 (worst case). Raw scores are the model outputs for LOCAR for each alternative. Normalized scores can be converted using the following equation (y = mx+b):

  Normalized Score (%) = (-0.392*Raw Score) + 100

- For SLE Damaging Flows (14-day ma flows above 1,700 cfs) triggered by basin runoff, the response curve is a line between the number of events from the LOSOM Iteration 1 period of simulation: 401 (target) and 468 (worst case). Raw scores are the model outputs for LOCAR for each alternative. Normalized scores can be converted using the following equation (y = mx+b):

  Normalized Score (%) = (-1.49*Raw Score) + 698.50

G.4.1.4 Caloosahatchee Estuary Final Array HUs

Table G-10 shows the RSM-BN model outputs for the ECB, FWO, and final array of LOCAR alternatives (Alternative 1, Alternative 2, Alternative 3) for the Caloosahatchee Estuary; the normalized scores for each; and average scores and HU conversion (average normalized score multiplied by 980 acres of oyster reef).

Table G-10. LOCAR Model Outputs, Normalized Scores, and Average Normalized Scores and Calculated Habitat Units for Each Alternative for the Caloosahatchee Estuary.

Salinity Envelope Performance Measure Metrics – 14-day ma Flow Events	LOCAR PM Raw Scores	Normalized (0-100%)
ECB		
Low Flows (<750 cfs)	549	33.16
Optimum (750-2100 cfs)	638	39.01
LOK Triggered Stress (High) (2100-2600 cfs)	77	73.79
Basin Triggered Stress (High) (2100-2600 cfs)	166	-7.79
LOK Triggered Damaging (>2600 cfs)	86	82.68
Basin Runoff Triggered Damaging (>2600 cfs)	230	-1.56
Average Score	36.55	-
Habitat Units	35,817	-
FWO		
Low Flows (<750 cfs)	752	-14.95
Optimum (750-2100 cfs)	549	19.27
LOK Triggered Stress (High) (2100-2600 cfs)	66	79.68
Basin Triggered Stress (High) (2100-2600 cfs)	124	46.75
LOK Triggered Damaging (>2600 cfs)	66	91.34
Basin Runoff Triggered Damaging (>2600 cfs)	160	107.81
Average Score	54.98	-
Habitat Units	53,884	-
Alternative 1		
Low Flows (<750 cfs)	586	24.39
Optimum (750-2100 cfs)	688	50.09
LOK Triggered Stress (High) (2100-2600 cfs)	42	92.51
Basin Triggered Stress (High) (2100-2600 cfs)	153	9.09
LOK Triggered Damaging (>2600 cfs)	55	96.10
Basin Runoff Triggered Damaging (>2600 cfs)	179	78.13
Average Score	58.39	-
Habitat Units	57,217	-
Alternative 2		
Low Flows (<750 cfs)	584	24.86
Optimum (750-2100 cfs)	686	49.65
LOK Triggered Stress (High) (2100-2600 cfs)	42	92.51
Basin Triggered Stress (High) (2100-2600 cfs)	154	7.79
LOK Triggered Damaging (>2600 cfs)	56	95.67
Basin Runoff Triggered Damaging (>2600 cfs)	178	79.69
Average Score	58.36	-
Habitat Units	57,195	-
Alternative 3		
Low Flows (<750 cfs)	586	24.39
Optimum (750-2100 cfs)	689	50.31

LOK Triggered Stress (High) (2100-2600 cfs)	41	93.05
Basin Triggered Stress (High) (2100-2600 cfs)	154	7.79
LOK Triggered Damaging (>2600 cfs)	55	96.10
Basin Runoff Triggered Damaging (>2600 cfs)	179	78.13
Average Score	58.29	-
Habitat Units	57,129	-

The best performing of the three LOCAR alternatives for the CRE, based on HU scores, is Alternative 1 (56,217 HUs).

G.4.1.5 St. Lucie Estuary Final Array HUs

Table G-11 shows the RSM-BN model outputs for the ECB, FWO, and final array of LOCAR alternatives (Alternative 1, Alternative 2, Alternative 3) for the St. Lucie Estuary; the normalized scores for each; and average scores and HU conversion (average normalized score multiplied by 434 acres of oyster reef).

Table G-11. LOCAR Model Outputs, Normalized Scores, and Average Normalized Scores and Calculated Habitat Units for Each Alternative for the St. Lucie Estuary.

Salinity Envelope Performance Measure Metrics – 14-day ma Flow Events	LOCAR PM Raw Scores	Normalized (0-100%)
ECB		
Low Flows (<150 cfs)	183	-6.80
Optimum (150-1400 cfs)	910	87.63
LOK Triggered Stress (High) (1400-1700 cfs)	30	86.43
Basin Triggered Stress (High) (1400-1700 cfs)	279	23.00
LOK Triggered Damaging (>1700 cfs)	41	83.92
Basin Triggered Damaging (>1700 cfs)	452	23.90
Average Score	49.68	-
Habitat Units	*21,561*	
FWO		
Low Flows (<150 cfs)	163	12.62
Optimum (150-1400 cfs)	997	123.43
LOK Triggered Stress (High) (1400-1700 cfs)	49	77.83
Basin Triggered Stress (High) (1400-1700 cfs)	238	42.25
LOK Triggered Damaging (>1700 cfs)	58	77.25
Basin Triggered Damaging (>1700 cfs)	344	185.09
Average Score	86.41	-
Habitat Units	*37,503*	*1*
Alternative 1		
Low Flows (<150 cfs)	209	-32.04
Optimum (150-1400 cfs)	1013	130.02
LOK Triggered Stress (High) (1400-1700 cfs)	20	90.95
Basin Triggered Stress (High) (1400-1700 cfs)	262	30.98
LOK Triggered Damaging (>1700 cfs)	29	88.63
Basin Triggered Damaging (>1700 cfs)	350	176.13
Average Score	80.78	-
Habitat Units	*35,057*	-
Alternative 2		

Salinity Envelope Performance Measure Metrics – 14-day ma Flow Events	LOCAR PM Raw Scores	Normalized (0-100%)
Low Flows (<150 cfs)	208	-31.07
Optimum (150-1400 cfs)	1011	129.20
LOK Triggered Stress (High) (1400-1700 cfs)	20	90.95
Basin Triggered Stress (High) (1400-1700 cfs)	261	31.45
LOK Triggered Damaging (>1700 cfs)	30	88.23
Basin Triggered Damaging (>1700 cfs)	350	176.13
Average Score	80.81	-
Habitat Units	*35,074*	-
Alternative 3		
Low Flows (<150 cfs)	210	-33.02
Optimum (150-1400 cfs)	1012	129.61
LOK Triggered Stress (High) (1400-1700 cfs)	20	90.95
Basin Triggered Stress (High) (1400-1700 cfs)	263	30.51
LOK Triggered Damaging (>1700 cfs)	27	89.41
Basin Triggered Damaging (>1700 cfs)	351	174.64
Average Score	80.35	-
Habitat Units	*34,872*	-

The best performing of the three LOCAR alternatives for the SLE, based on HU scores, is Alternative 2 (35,074 HUs). **Section 5.3.3** of the main report discusses the performance of alternatives, including the sensitivity analysis conducted to compare a FWO scenario with different Lake Okeechobee operations. The FWO results presented here are based on currently authorized operations.

G.4.2 Northern Estuaries Alternative Performance

Table G-12 shows the combined Northern Estuaries HUs and potential lift compared to the ECB and FWO. The PMs for each estuary are combined with equal weighting. Combined, the best performing alternative is Alternative 1 at 92,274 HUs, but only marginally so compared to Alternative 2 at 92,269 HUs and Alternative 3 at 92,001 HUs. The HUs for the Northern Estuaries are combined with the Lake Okeechobee HUs for the CE/ICA analysis. The CE/ICA is evaluated in **Section G.5**.

Table G-12. Combined Northern Estuaries HUs for the Final Array of Alternatives.

Region	ECB	FWO	Alternative 1	Alternative 2	Alternative 3
Caloosahatchee HUs	35,817	53,884	57,217	57,195	57,129
St. Lucie Estuary HUs	21,561	37,503	35,057	35,074	34,872
Overall Northern Estuaries HUs	57,378	91,387	92,274	92,269	92,001
Potential Lift from FWO	N/A	N/A	887	882	614
Potential Lift from ECB	N/A	34,009	34,896	34,891	34,623

Note: The Northern Estuaries lifts were calculated as the difference between the FWP and FWO, and between FWP and ECB over the period of analysis.

G.5 Summary of Alternative Performance

Cost effective/incremental cost analysis (CE/ICA) is an analytical methodology to assess and compare environmental restoration costs and benefits. The LOCAR CE/ICA uses HUs (the acres of aquatic habitat the project creates or improves) and project cost to determine the cost-effectiveness and incremental costs. The objective of CE/ICA is to support scientifically sound, informed decision-making and financial investment.

The CE compares each plan's restoration potential (represented by HUs) and total cost. This comparison determines which plan produces the same number of or more HUs at a lower cost or more HUs at the same cost. The ICA uses the HUs and costs to identify the per-HU cost associated with each plan. This comparison is further refined by annualizing HU gains to quantify AAHUs used to forecast changes in habitat value and quantity over the project life span (see **Figure G-17**).

The CE/ICA analysis was conducted using the Institute for Water Resources (IWR) Planning Suite, which is the Corps' certified CE/ICA procedures software. Inputs from the Planning Suite tailor the model to each project and identify plan break points, where significant positive or negative changes in project restoration outputs or investment occur.

CE/ICA outputs from the IWR Planning Suite are integral to determining the NER plan. The NER plan is the:

> …justified alternative & scale having the maximum excess of monetary & non-monetary beneficial effects over monetary & non-monetary costs… (that) occurs where the incremental beneficial effects just equal the incremental costs, or alternatively stated, where the extra environmental value is just worth the extra costs... (ER 1105-2-100, *Planning Guidance Notebook*, Appendix E-28.e(1)).

The NER plan can be influenced by other factors, such as partnerships, but generally it reasonably maximizes restoration benefits, is demonstrated to be cost-effective, has comparable cost per HU, and satisfies other Corps project criteria.

The CE/ICA was used to support selection of the Recommended Plan by demonstrating each plan's HUs and costs relative to other plans, the FWO condition. HUs are used to compare Project alternatives to the FWO for each habitat zone and for the total Project Area (**Table G-13**). **Figure G-17** displays storage AAHU by alternative, and **Figure G-18** presents the cost-effectiveness of the plan alternatives in terms of annualized habitat costs versus HUs. The storage CE/ICA identifies that Alternatives 1 and 2 are best-buy alternatives. The results are displayed in **Table G-14**.

Table G-13. Total HUs for Each Storage Alternative.

Project Region	ECB	FWO	Alternative 1	Alternative 2	Alternative 3
Total Lake Okeechobee	250,073	274,335	328,902	330,369	327,822
Caloosahatchee Estuary	35,817	53,884	57,217	57,195	57,129
St. Lucie Estuary	21,561	37,503	35,057	35,074	34,872
Total Northern Estuaries	57,378	91,387	92,274	92,269	92,001
Total HUs	307,451	365,722	421,176	422,638	419,823

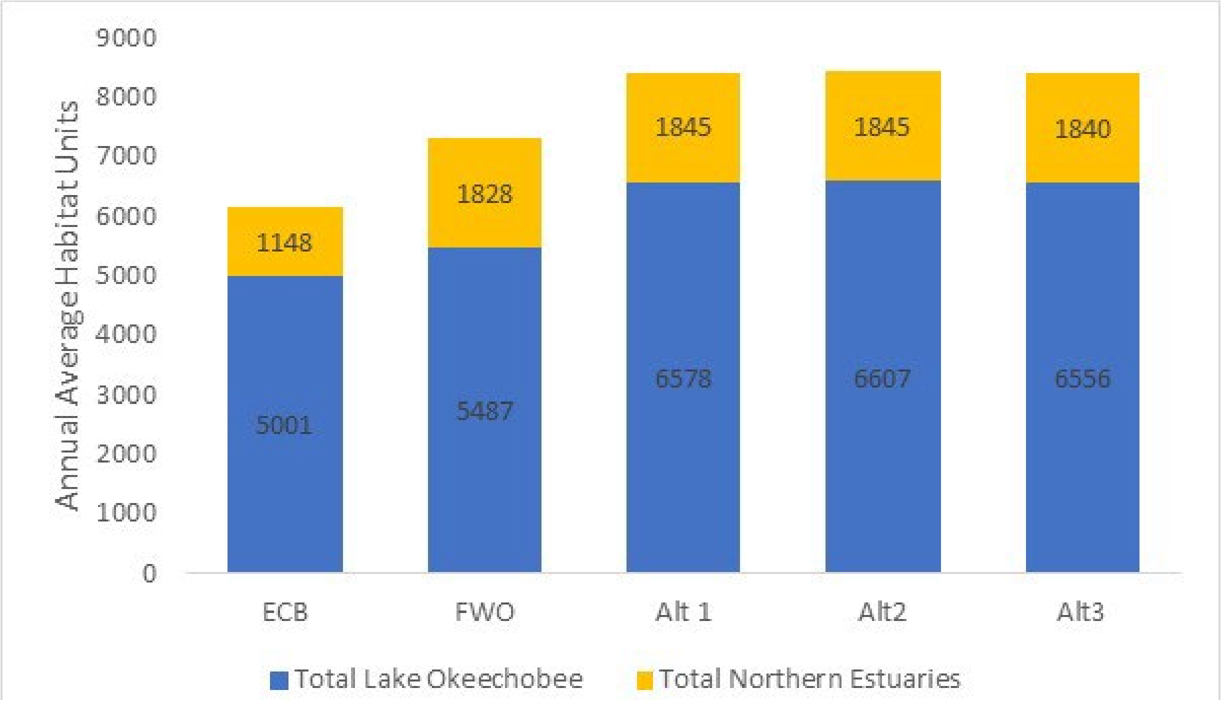


Figure G-17. Annual average habitat units.

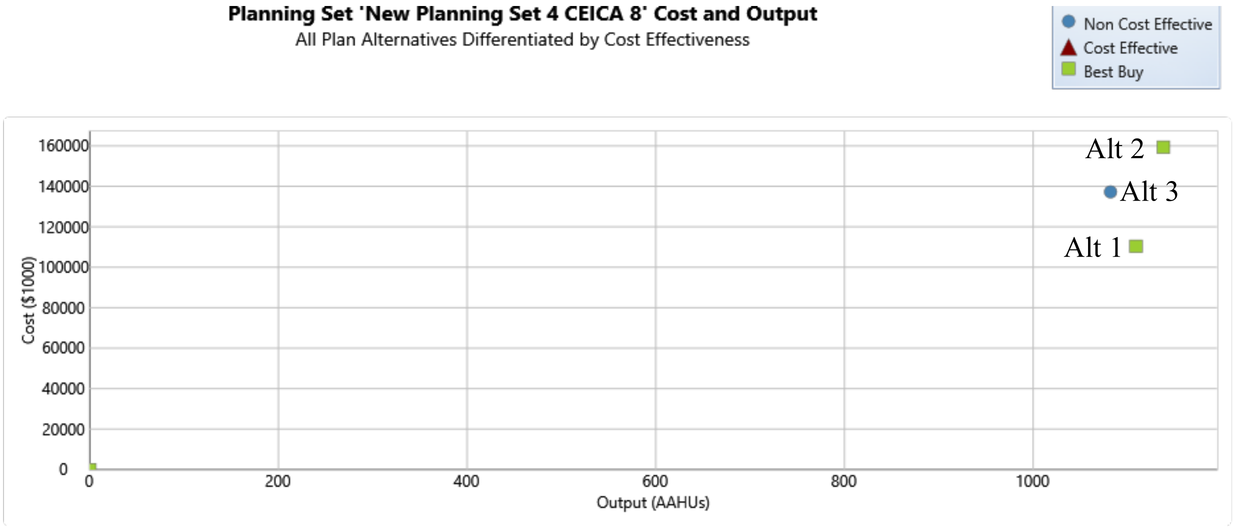


Figure G-18. Annual average costs versus annual average habitat units to illustrate alternative cost-effectiveness.

Table G-14. Cost-effectiveness and Incremental Cost Analysis Inputs

Category	ECB	FWO	Alternative 1	Alternative 2	Alternative 3
AAHUs	6,149	7,314	8,424	8,453	8,396
Difference from FWO	-	-	1,109	1,138	1,082
Annual Average Cost	-	-	$61,198,304	$92,780,560	$74,211,792
Result	-	-	Best Buy	Best Buy	Not Cost Effective

G.6 Technical Quality of the Planning Model

The planning model depends on dynamic regional hydrologic and ecologic models used to calculate environmental benefits. The environmental benefits are based on inputs derived from the RSM-BN and the working hypotheses set forth in the Lake Okeechobee and Northern Estuaries Conceptual Ecological Models (Barnes 2005, Sime 2005). These models are considered appropriate tools for planning for the CERP. The RSM-BN has been validated through the Corps Engineering Model Certification process established under the E&C SET initiative. Each of the Project PMs for the storage component of the planning effort described above were derived from those PMs approved for use by RECOVER. The scientists of RECOVER have extensive experience working in South Florida and Everglades wetlands ecosystems. These members are considered by their peers to be the experts in their fields. In addition, the conceptual ecosystem models from which the PMs were developed have been extensively peer reviewed and provide the framework for the planning and assessment of the CERP.

The basins version of the RSM model is a long-term water balance model that considers basins as large waterbodies with homogeneous properties and negligible variability of hydrologic properties of interest. Traditionally, these models have been used for reservoir capacity design problems where the capacities are large and long-term basin outflow time series are known at large time steps. Spatial variability of parameters and state variables within basins are not available or not critical for these problems where the focus is the storage behavior in the recipient waterbody. Long-term water balance models are not capable of providing spatially varying hydraulic state variables such as water levels or flow distributions within the basins. They cannot provide short-term variability of outflow releases since small-scale hydraulic behaviors are not simulated in these models. Total error consists of input data errors, model structure errors (algorithm), and parameter errors. With water balance models, you have a potential to have large structure errors when focusing on small-scale features or short-term fluctuations because some of the mechanics (algorithms) are not there. But by design, the objective is to focus on long-term variations and large spatial extents. For such spatial and temporal solutions of interest, the error is small.

The RSM-BN assumes that water in each waterbody is held in level pools. The model domain covers five major watersheds: Kissimmee River, Lake Okeechobee, St. Lucie River, Caloosahatchee River, and EAA, the latter being the latest addition. The watersheds are further divided into sub-watersheds until fundamental waterbodies can be considered as separate model nodes. Individual operating rules were encapsulated into the model that define how water is moved between two nodes. Taken together, the set of management rules defines the linkage of all nodes within the model domain. It is important to note that RSM-BN has successfully been used in project planning support for both State of Florida and CERP initiatives previously. RSM-BN has also undergone many independent scientific reviews and has received formal engineering model certification by the Corps and is approved for use in LOCAR. The computational methodology of RSM-BN uses a “water budget” approach that significantly reduces model error typically found in mesh-based models.

Output from RSM-BN are typically post-processed into project PMs and used in a comparative manner to evaluate the differences between current, no action, and a range of potential future project actions being contemplated. The primary emphasis of the evaluation involves PMs associated with Lake Okeechobee stage and flows to the Northern Estuaries. Given the intended use of RSM-BN in this study, an effort was undertaken to evaluate how sources of model error and uncertainty may affect model outputs and Project decision-making.

The RSM-BN is an excellent tool for assessing the water budget interaction in a complex hydrologic system and an effective tool in comparing the relative performance of proposed alternatives. In addition, it is generally assumed that relative performance of proposed alternatives is of equal credibility and reliability. The study planning process assumed that each performance measure used within the Project Area could be extrapolated from point locations simulated by alternative plans to larger areas they represent. It also assumed that results from hydrologic models were similar across spatial scales within these geographic regions. Due to differences in model accuracy and precision (within and among regions of each model domain), differences in sensitivities of each performance measure to changes in hydrologic conditions, the assumption that all PM results are of equal credibility could be viewed with skepticism. To address this concern, the modeling team developed and applied a methodology to validate the robustness of RSM-BN at decision-making. The analysis verified that observed differences between alternatives were not the result of differential exploitation of hydrologic model error/bias.

G.7 RECOVER Approved Performance Measures

The full, approved Lake Okeechobee Performance Measure Documentation Sheet and Northern Estuary Performance Measure Documentation Sheet are at the end of this appendix.

G.8 References

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Attachment G-1: Lake Okeechobee Performance Measures

Lake Okeechobee Performance Measure
Lake Stage

Last Date Revised: March 4, 2020

Acceptance Status:

1.0 Desired Restoration Condition

In most years, lake stage will vary within an "envelope" based on the annual hydrograph described below. Stages will mimic historic conditions by receding from wet season highs (approx. Nov-Jan) to dry season lows (approx. May-Jun), with recession rates generally increasing along with evapotranspiration rates through the dry season. These rates would typically vary from 0 – 0.07 ft/wk (0.02 m/wk) early in the season up to 0.16 ft/wk (0.05 m/wk) later in the dry season. Stages will ascend at moderate rates (<0.25 ft/wk) (0.08 m/wk) back to seasonal highs. The ecological envelope generally encompasses stages from 11.5 – 15.5 feet (3.51 – 4.72 m) (National Geodetic Vertical Datum 29 throughout) and allows for seasonal fluctuation around a 12 – 15 feet (3.66 – 4.57 m) stage target. The ecological envelope varies between Normal or Recovery conditions (see **Figure 3A** and **Figure 3B**), depending on whether impacts from high-water or tropical storm events necessitate lower stages for vegetation recovery. When lake stages do occur outside of the stage envelope, they would not go above or below extreme stage thresholds, defined as 17 ft (5.18 m) and 10 ft (3.05 m), respectively. In the desired restoration condition, there will not be frequent (semi-annual) or prolonged (several months) departures of lake stage outside of the defined envelopes and the occurrence of extreme high or low lake stage events will be rare (once per decade or less).

1.1 Predictive Metric and Target

The target for the lake is for stages to remain within the desired envelope (12 – 15 feet); and if stages do deviate, to at least avoid extreme (>17 ft [5.18 m] or <10 ft [3.05 m]) stages; resulting in a score of zero points and no extreme stage exceedances. Points are assigned during evaluation of lake stages as they deviate from the desired envelope, as well as when extreme highs (>17 ft [5.18 m]) or lows (<10 ft [3.05 m]) are exceeded. Extreme stage exceedances are calculated separately from lake envelope scores, resulting in evaluation metrics for the ecological envelope, extreme high, and extreme low stages. This Performance Measure supersedes and addresses LO-3 Lake Okeechobee Stage Envelope (Last Date Revised: Mar 7, 2007).

1.2 Assessment Parameter and Target

Daily lake stages (as modeled or reported by the US Army Corps of Engineers [USACE]) will be assessed relative to the seasonally fluctuating lake stage envelope (described below), as well as relative to extreme stages (defined above). The target is the same as described in 1.1.

2.0 Justification

2.1 An Ecological Envelope of Seasonally Variable Water Levels

A wide body of research has documented the benefits of variable water levels in littoral and wetland ecosystems (see Mitsch and Gosselink 2000 for detailed overview). The hydrology, or the seasonal, annual, and interannual drying and wetting of marshes, makes these systems among the most productive in the world (e.g. Junk et al. 1989) and drives a suite of critical processes; oxygen levels, nutrient types and availability, floral and faunal reproductive cycles, and ultimately how plants and animals are distributed on the landscape. In a general sense, the hydrologic gradient (or the elevation slope of littoral marshes) is occupied by a suite of organisms with varying tolerances to flooding or inundation depth. Wetter periods, among other things, can; reduce the presence of flood intolerant species (e.g. woody plants) at higher elevations, improve foraging access for aquatic predators, protect nesting areas for species like wading birds, snail kites (*Rostrhamus sociabilis*), alligators, and sport fish, and reduce the density of emergent plants at lower elevations. Drier periods, on the other hand, expose marsh soils and reduce accumulated muck, promote fires to reduce dead biomass and increase plant diversity, and provide necessary regrowth periods for habitat that is stressed during wetter periods (lower elevation marshes, submerged plants, nesting substrate for wading birds and snail kites, etc.). These wet and dry periods have tradeoffs associated with each, and the magnitude, duration, and return frequency of these events are critical to the health of the ecosystem.

Historically, littoral marshes of Lake Okeechobee expanded well outside the current footprint of the lake, with high-water events pushing the lake laterally into short hydroperiod wetlands in the surrounding watershed. Since construction of the levee (Herbert Hoover Dike), littoral marshes are restricted within the lake's current footprint. If lake stages are managed too high, the entire marsh retreats upslope, extirpating shorter hydroperiod wetlands at high elevations. If lake stages are managed too low, high elevation marshes transition to terrestrial communities, and the entire marsh moves downslope. Currently, the littoral marsh generally occupies elevations from the base of the surrounding levees (15 ft [4.57 m]) to roughly 12 ft (3.66 m) in elevation (Havens 2002), though fringing stands of bulrush and aquatic grasses can extend to around 10 ft (m) in elevation (Graham et al. 2020), and beds of submerged vegetation to 8 or 9 ft (2.44 – 2.74 m), when conditions allow (Havens et al. 2004). Lake stage has a profound effect on the health of these littoral marshes and the lake in general (Havens 2002), not just due to direct hydrologic relationships; but to the varying connectivity of the central, muddy portion of the lake to littoral and nearshore areas at different lake stages (Havens 1997). Seasonally variable water levels within the range of 12.0 ft (3.66 m) as a June-July low and 15.0 ft (4.57 m) as a November-January high have been supported by numerous studies (Johnson et al. 2007, Havens and Gawlik 2005, Havens 2002) as the best tradeoff between wet and dry conditions on the lake, supporting short- to long-hydroperiod communities and capturing key parameters. For example;

- Seasonal (winter) high water levels (near 15.0 ft [4.57 m]) inundate nesting and foraging habitats for wading birds (Smith and Collopy 1995), while water levels near 14.0 ft (4.27 m) in mid-March support peak snail kite nest initiations (Fletcher et al. 2017)
- Falling water levels from near 15.0 ft (4.57 m) in late winter to 12.0 – 13.0 ft (3.66 – 3.96 m) in the spring concentrates prey resources in the littoral zone for improved wading bird foraging and nesting (Chastant et al. 2017, Smith et al. 1995)
- Water levels near 12.0 ft (3.66 m) benefit submerged plants and bulrush (*Schoenoplectus californicus*) at the outer edges of the marsh by reducing light attenuation in the summer months

and promoting growth of underground biomass for survival during turbid, high water events (Harwell and Sharfstein 2009, Havens et al. 2004, and **Appendix A**)

- A natural rocky reef in the southern portion of the lake isolates turbid, pelagic water from large areas of nearshore zone at a lake stage of around 14 ft (4.27 m) and under. This helps improve water clarity, promotes submerged plant coverage, and reduces phosphorus levels in the nearshore zone in the southern region of the lake from near Clewiston to Pelican Bay (Havens and Walker 2002)
- Seasonal variation of the envelope results in annual flooding and drying of most of the marsh, which favors development of a diverse emergent plant community (Richardson et al. 1995, Keddy and Frazer 2000) and reduces muck accumulation.
- Interannual variability (width of the envelope) of high and low lake stages allows drier and wetter years, driving productivity and balancing tradeoffs between good nesting years (e.g. wading birds and snail kites, littoral marsh prey production) and habitat recovery/maintenance years (e.g. submerged plants, bulrush, woody nesting substrates)

2.1.1 Updates to Original (2007) Performance Measure Envelope

As described above, there is a wide body of research that supports seasonally varying stages of 12.0 ft – 15.0 ft (3.66 – 4.57 m), including the work cited to support the original envelope (Havens 2002). The 2007 ecological envelope was created by adding a 0.5 ft buffer to stages varying from 12.5 ft - 15.5 ft (3.81 – 4.72 m), resulting in an envelope of 12.0 ft – 16.0 ft (3.66 – 4.88 m); the top of which was a foot higher than specified in earlier studies (see also Havens and Gawlik 2005). Since its development, turbidity (a measure of light attenuation) has been increasing over time, likely due to major hurricanes that passed over the lake in 2004, 2005, and again in 2017 (Betts et al. 2020). The first storms were found to have loosened the sediment bed (Jin et al. 2011), making more material suspendable during subsequent storms (e.g. cold fonts). This effect appears to be long-lasting, leading to elevated turbidity for many years post-storm and affecting lower elevation marshes at a wider range of lake stages.

The status of various parameters of lake ecological health have been reviewed most recently as part of the RECOVER 2019 System Status Report (SSR) for the period May 2012 – April 2017 (RECOVER 2019). The indicators included water quality parameters, SAV, sportfish populations, wading bird nesting, and marsh vegetation composition. Overall, most indicators were described as in poor to moderate condition, or trending in the wrong direction. This contrasted with hydrologic targets, as lake stages during the period were much closer to the 2007 ecological envelope relative to the previous five-year period (2007 – 2012). The report found that while the magnitudes of lake stages were fairly similar to the 12.5 ft - 15.5 ft (3.81 – 4.72 m) range (**Figure 1**), stages exceeded 16.0 ft (4.88 m) in every water year (e.g. WY2017 = May 1, 2016 – April 30, 2017) of the evaluation period (note **Figure 1** only shows monthly averages). Further, the seasonality of the water levels varied considerably from the envelope, particularly during the growing season (**Figure 2**). From roughly June–October, for example, lake stages exceeded the envelope by 1.0 – 2.5 ft (0.3 – 0.76 m) in 2013 and 2016, at a critical period for plant growth and algal bloom formations; likely having a disproportionate impact due to the timing of higher water levels. Further, due to increasing trends in turbidity, summer stages may need to be lower now for the same level of benefit than when the 2007 envelope was developed.

The top of the new envelope was adjusted downward roughly 0.5 ft (0.15 m) in the winter and early spring periods to more closely align with studies cited earlier, and the top and bottom of the envelope were adjusted downward in the summer period to capture the importance of lower summer stages for light penetration in the water column, particularly as turbidity has increased. The envelope is wider in the March-April and October time frames, capturing the importance of interannual variability in terms of wetter and drier years. The resulting envelope varies around a 12.0 ft – 15.0 ft (3.66 – 4.57 m) seasonally variable stage, ranging from 14.5 ft – 15.5 ft (4.42 – 4.72 m) in the winter and from 11.5 ft – 12.5 ft (3.51 – 3.81 m) in the summer.

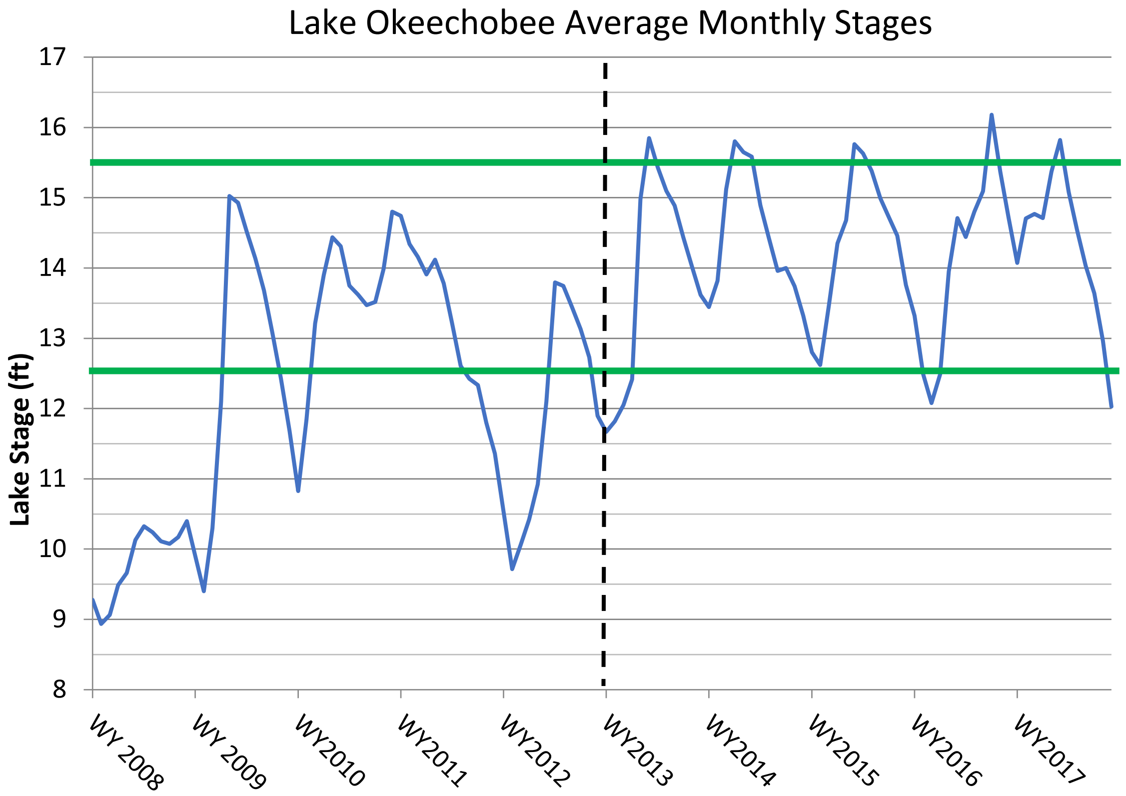

Figure 1. Lake Okeechobee average monthly stages from water year (WY) 2008 – 2017, or May 1, 2007 to April 30, 2017, using USACE average lake stage. Green horizontal lines indicate the top and bottom stages of the original ecological envelope and the vertical line is where WY2013-2017 period begins.

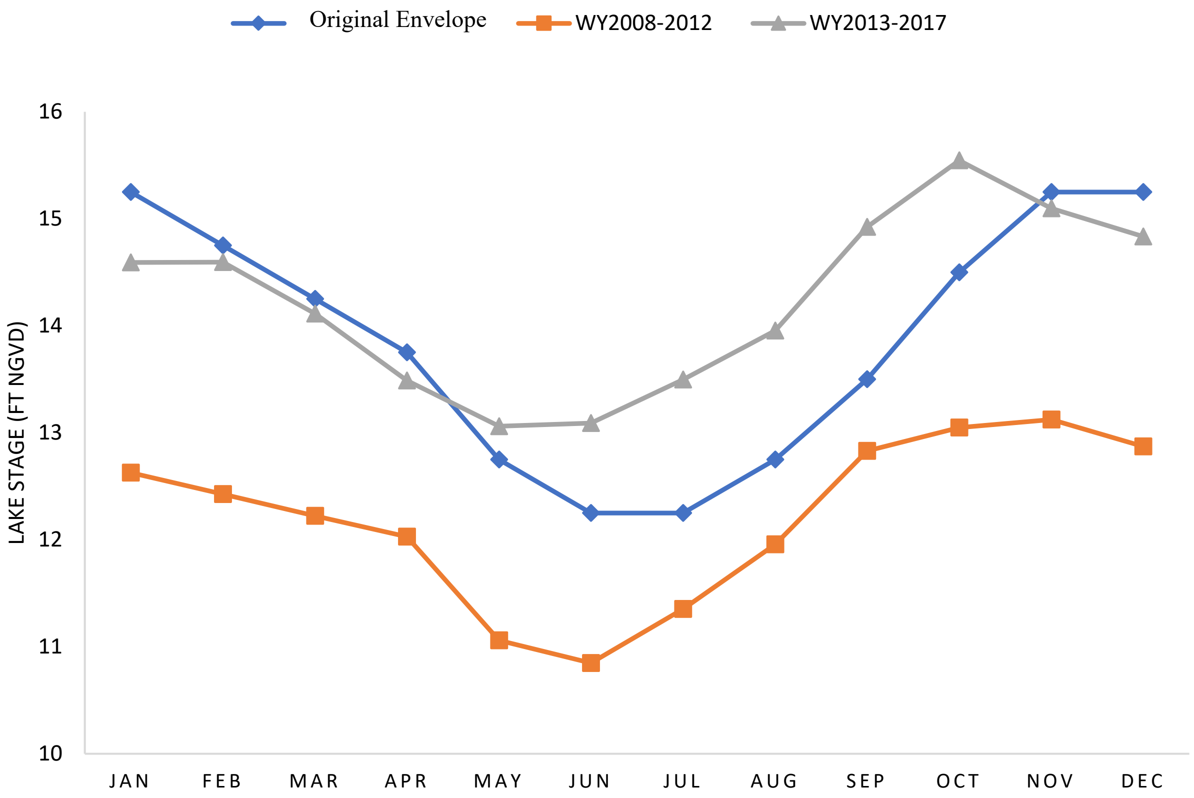

Figure 2. Average monthly lake stage for the original ecological envelope (blue), for WYs 2008-2012 (orange), and WYs 2013-2017 (gray), using the USACE average lake stage.

2.2 Extreme Lake Stage Impacts

While frequent deviations from the ecological envelope can have chronic impacts, acute effects occur from extreme lake stages. Extreme high (>17 ft [5.18 m]) and low (<10 ft [3.05 m]) water levels can have multi-year impacts on the littoral and nearshore areas of Lake Okeechobee. See Havens (2002) and Havens and Gawlik (2005) for summaries of the biological underpinnings of these effects. Examples are discussed below.

2.2.1 Extreme High

Extreme high stages (>17 ft [5.18 m]) allow wind-driven waves to directly impact the nearshore emergent and submerged plant communities, causing physical uprooting and creation of organic berms that impede hydrologic connectivity and movement of fish and wildlife (Havens and Gawlik 2005). High stages promote the transport of suspended solids and associated nutrients from the mid-lake region (where unconsolidated sediments are thickest) into the shoreline regions; reducing water clarity and light penetration, increasing nutrients, and reducing SAV and emergent plant densities (further destabilizing sediments and releasing more nutrients) (James and Havens 2005). High stages also allow deposition of unconsolidated mud into nearshore regions, covering sand and peat sediments and reducing their suitability for SAV. High stages transport nutrient-rich water into higher elevation littoral marshes where changes in periphyton biomass and taxonomic structure can occur, as well as expansion of invasive vegetation like cattail (*Typha* spp.). High stages reduce coverage of woody species that are important for wading bird and snail kite nesting, promote conversion of spikerush (*Eleocharis* spp.) prairies to lily habitat, and reduce coverage of high marsh grasses like cordgrass (*Spartina bakeri*) (Zhang and Welch 2018). High stages reduce foraging habitat and prey density for wading birds (Smith et al. 1995) and reduce nesting effort for both wading birds (Chastant et al. 2017) and snail kites (Fletcher et al. 2017). Wading bird foraging is limited by water depth, and virtually the entire marsh is too deep for even long-legged wading birds (e.g. great egrets, great blue herons, woodstorks) at stages >16.0 ft (4.88 m). Associated changes in habitat structure, like loss of SAV and associated prey, also reduce fish diversity, populations, and biomass (Rogers and Allen 2008). Overall, high lake stages result in loss of submerged plants, low-elevation emergent plants, reductions in fish populations, undesirable shifts in marsh vegetation composition (Sharfstein and Zhang 2017), and shifts in the macroinvertebrate community to those representative of disturbed ecosystems (Warren et al. 1995).

2.2.2 Extreme Low

Extreme low stages (<10 ft [3.05 m]) also have multiple negative impacts to lake health. Most of the littoral marsh is dried when lake stages are <12 ft (3.66 m), and at <10 ft nearly the entire shoreline fringing bulrush zone and much of the lake area that would otherwise support submerged vascular plants also dries out. These low stages encourage invasion or expansion of exotic or nuisance species at both high (e.g. torpedograss [*Panicum repens*], Brazilian pepper [*Schinus terebinthifolia*], punk tree [*Melaleuca quinquenervia*]) and low elevations (e.g. cattail, common reed [*Phragmites australis*], tropical American water grass [*Luziola subintegra*]); and displace desirable habitats like spikerush (Sharfstein and Zhang 2017). Prolonged extreme low stages, like those experienced in 2007 – 2008, can shift areas of former open-water or SAV to dense stands of emergent plants (e.g. cattail), resulting in long-term conversion (>10 yrs) of habitat, increased muck accumulation, and the need for large-scale management activities for restoration (Zhang and Welch 2018).

Low lake stages also result in direct losses of habitat that can severely limit or even eliminate entire breeding seasons for many species of fish and wildlife. Snail kites and wading birds, for example, have shown reduced or no nesting on the lake at extreme low lake stages (Chastant et al. 2017, Fletcher et al. 2017), which can have population-wide effects during regional droughts (Fletcher et al. 2018). These impacts are severe and long-term for short lived species like the native Florida apple snail (*Pomacea paludosa*), which require water to reproduce and cannot survive dry conditions for more than several months (Darby et al. 2004). Exposing peat substrates in southern portions of the lake can also degrade habitat for the endangered Okeechobee gourd and increase risk of peat fires, leading to a permanent loss of marsh elevation.

2.3 Recovery from Extreme Events

Ecological recovery from extreme high or low lake stages can be slow, requiring multiple years of appropriate stage regime to recover. Recovery from low lake stages can be expedited primarily through habitat management activities; removing exotic or invasive species with selective use of herbicides (Welch et al. 2019), restoring diversity and structure through prescribed fire, or using a combination of both (Zhang and Welch 2018). Large-scale management of cattail in Moonshine Bay, for example, led to dramatic increases in wading bird and snail kite activity in subsequent years (Sharfstein and Zhang 2017, Fletcher et al. 2017), after low lake stages promoted cattail expansion into former water lily-dominated habitats. Similarly, burning and spraying torpedograss at high marsh elevations has restored thousands of acres of spikerush and beakrush (*Rhynchospora* spp.) habitat over the past decade (Sharfstein et al. 2015).

Recovery from extreme high lake stage events can be expedited with low lake stages, as documented for submerged plants (Havens et al. 2004, Jin and Ji 2013, and **Appendix A**) and for sport fish (Havens et al. 2005). Most evidence of recovery has been from extreme low events (< 10 ft [3.05 m]) during regional droughts (2001, 2007, 2008, 2011), but recent evidence from 2019 shows benefits of even moderate low stages (see **Appendix A**). Light penetration improves non-linearly on Okeechobee as stages decline due to the combination of reduced depth, shoreline bathymetry, reduced turbidity, reduced phytoplankton growth, and positive feedbacks to water clarity as SAV coverage expands. Therefore, impacts from high-water events are reduced both in duration and extent when followed by low lake stages. Lower water levels, while posing their own risks, promote recovery of habitat (and subsequently, fish and wildlife) in several ways;

- Woody species (e.g. willow [*Salix* spp.]), which are important nesting substrate for wading birds and snail kites, require periodic drying to withstand high stages or prolonged flooding
- Important, indicator vegetation like giant bulrush have optimal growth conditions at stages between 10 – 12 ft (3.05 – 3.66 m) (Harwell and Sharfstein 2009)
- Dried marshes promote prescribed fire management, reduction of muck and accumulated organic material, and germination of short hydroperiod communities
- Increased light penetration in nearshore zones prompts germination and expansions of SAV and increased densities of desirable native plants like deep-water grasses (*Paspalidium geminatum*, *Panicum hemitomon*)
- Higher stem densities and associated periphyton further improve water clarity and reduce phytoplankton, creating positive feedbacks for recovery of vegetation at even lower elevations
- Natural shoreline bathymetry isolates nearshore zones from turbid water in the central mud regions of the lake, further improving light penetration (Maceina 1993, James and Havens 2005, Havens 1997)

2.3.1 A Recovery Envelope

For the reasons listed above, we have developed two ecological envelopes; one for normal conditions (Normal Envelope), and one for lower stages (Recovery Envelope) following years with high-water impacts. The 2007 version of the Lake Stage Envelope Performance Measure recognized the importance of infrequent low stages but did not specify targets; rather, it simply stated stages <11ft (3.35 m) for 90 days once per decade would be beneficial for a variety of reasons. Such events, usually occurring during regional droughts, are critical for long-term maintenance of woody species in the marsh, for large-scale fire management, oxidation of organic soils, habitat restoration projects, etc. but do not address acute impacts from high lake stages. For example, widespread losses of SAV communities have recurring impacts to fish, invertebrates, and water quality year after year until the community recovers. Moderate low lake stages after high-water events speed the rebound of these communities. This Performance Measure updates the Normal Envelope (**Figure 3A**) and establishes a Recovery Envelope (**Figure 3B**). The use of two envelopes allows for variable targets based on antecedent conditions and defines the timing, duration, and frequency of low water events. These were specific recommendations by the University of Florida Water Institute for improvements to RECOVER hydrologic performance measures (Graham et al. 2020).

The Recovery envelope would be triggered when high water events are likely to cause substantial stress to SAV or reductions in coverage if not followed by optimal growing conditions the following year. Historically, such events are related to hurricanes, extreme highs (>17 ft [5.18 m]), or high summer stages (Welch et al. 2019). The macroalgae muskgrass (*Chara* spp.) is a good indicator of SAV growing conditions on the lake (Harwell and Sharfstein 2009), dramatically increasing areal coverage when light penetration is high (Havens et al. 2002, 2004). The lowest coverage of this species is related to 30-day minimum summer stages >13.0 ft (3.96 m) (see **Appendix A**). Therefore, a shift from Normal to Recovery envelope (starting Jan 1) would occur when:

- Stages are >17 ft (5.18 m) at any time of the year (e.g. 2003, 2004, 2005, 2017)

OR

- The 30-day minimum lake stage (elevations exposed for at least 30 days nonconsecutively) in the June 1 – July 31 window is >13.0 ft (3.96 m), which represents the years (excluding hurricanes) with the lowest coverage of *Chara* on record (2003, 2010, 2013, 2016)

The thresholds for a shift back to the Normal envelope would similarly be related to SAV coverage, i.e. whether stages were low enough for long enough to allow sufficient germination, growth, and expansion of the populations to survive higher water in the winter and subsequent years. Earlier studies suggest that extreme low stages dry out areas that would otherwise be colonizable by vascular SAV species, and that a more diverse community may not establish until 1-2 years after extreme low stages. Moderately low stages, however, recently produced rapid expansions of vascular and macroalgae SAV, with peak vascular biomass occurring roughly at elevations that were dried or nearly dried out in the summer of 2019 (see **Appendix A**). The thresholds below roughly correspond to those conditions. However, when heavy rainfall and/or tropical systems impact the lake after low stages, much or all of the recovery process can be lost, as was observed in 2017 (low stages followed by rapid ascension rates and then Hurricane Irma) (Welch et al. 2019).

Therefore, a shift from Recovery to Normal envelope (starting Jan 1) would occur when:

- Lake stages are below 12 ft (3.66 m) for 90 days (nonconsecutively) between Apr 15 and Sep 15

  OR
- Stages are below 11.5 ft (3.51 m) for 60 days (nonconsecutively) between May 1 and Aug 1
- One of above criteria are met **AND** Lake stages do not exceed 16 ft (4.88 m) before Jan 1

While these transition thresholds appear rigid, specific criteria must be defined for evaluating model outputs associated with CERP or other restoration projects. If these targets are used to inform lake management decisions, they should be accompanied with in-lake ecological monitoring to evaluate real-time conditions of indicator communities.

The resultant ecological envelopes (**Figure 3A and B**) encompass several important features. The envelopes themselves capture the inherent tradeoffs between wet and dry years, and even wet and dry seasons within littoral habitats. Flooded marshes teem with productivity and support reproductive cycles of many species of fish and wildlife, but the act of flooding and drying drives nutrient cycles, plant distribution and composition, and makes wetland ecosystems among the most productive in the world (see Junk et al. 1989, Mitsch and Gosselink 2000). When lake stages are near the top of the envelopes, more inundated habitat is available, driving higher prey production, wading bird nesting, snail kite nesting, etc. When stages are near the bottom of the envelopes, aquatic prey will be concentrated, plants will sprout and build root storage, and organic material will decompose. While the envelopes appear very specific in terms of stage requirements throughout the year, the general shape reflects a broad literature review and the best professional judgement of working group members (see Section 8.0) using monthly time-steps. Variations in the width of the envelope generally encompass the degree of desired flexibility (or interannual variability), while variations in slope are related to desired recession/ascension rates or a function of linear extrapolations between average monthly stage targets. Additionally, non-linear scoring calculations around the envelope capture whether various stage targets are gradual or abrupt thresholds in terms of potential biological impacts; and define the importance of various stages throughout the year (see Evaluation Application below in 4.0). Overall, these envelopes represent the importance of several factors:

- High lake stages (14.5 – 15.5 ft [4.42 – 4.72 m]) at the end of the wet season or into winter (November – January) provide inundation of high elevation marshes, maximizing wetland extent and aquatic habitat prior to the dry season and breeding season for many species of fish and wildlife (e.g. wading birds, waterfowl, snail kites, fish and invertebrate prey production, etc.)
- Moderate stage recessions (<0.16 ft/wk [0.05 m/wk]) throughout the spring avoid stranding breeding fish and wildlife but serve to concentrate prey
- A wider envelope in the March – June time frame reflects the importance of inter-annual variability and the inherent tradeoff between high and low stages in the breeding season of many species; maximizing habitat inundation in some years with habitat rejuvenation in others

- Seasonal lows (11.5 – 12.5 ft [3.51 – 3.81 m]) in the summer provide maximum light penetration into the water column at the peak of the growing season and when turbidity is lowest (wind speeds are lowest in summer), providing critical growth and root storage for SAV and low elevation marsh communities like bulrush. At high elevation, organic soils are oxidized and woody species, annuals, and short hydroperiod species germinate or rejuvenate
- Moderate ascension rates (<0.25 ft/wk [0.08 m/wk]) throughout the majority of the wet season reduce flooding of alligator nests, snail kite nests, and apple snail eggs, while allowing SAV and emergent plant growth to keep up with rising water and reduced light penetration.
- Greater flexibility in the September – November season reflects the variability in wet season rainfall and the importance of inter-annual variability
- Following impacts from high lake stages, lower stage targets (as defined by the Recovery Envelope) expedite recovery of littoral habitat and fish and wildlife communities
- The width of the envelopes represents inherent tradeoffs between wet and dry years; e.g. allowing for drier conditions that rejuvenate low elevation marshes and woody species, and wetter conditions that promote prey production and wading bird/snail kite nesting.

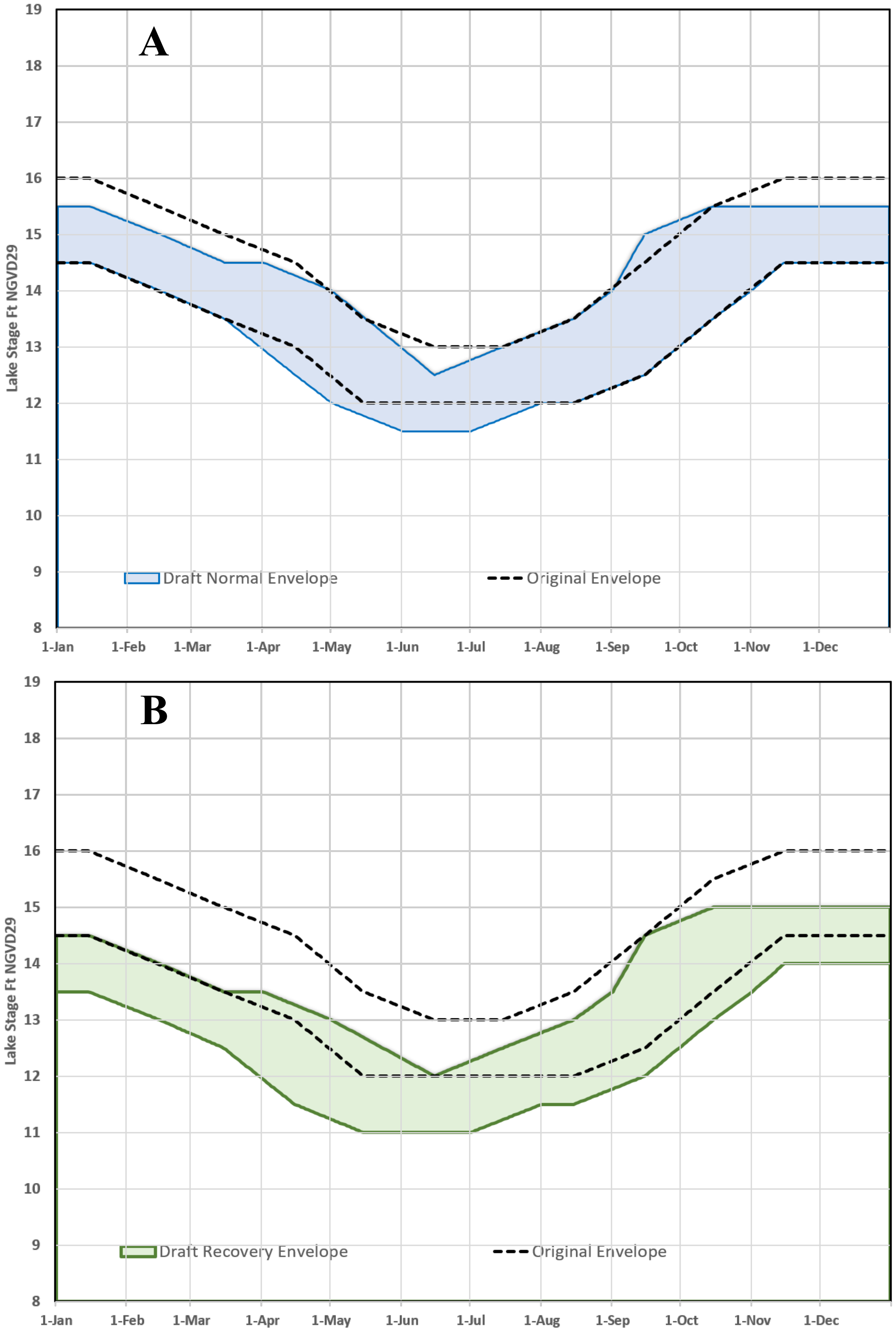

Figure 3. The original 2007 envelope (dashed) is shown relative to the **(A)** draft Normal envelope in blue and **(B)** the Recovery envelope in green.

3.0 Scientific Basis

Lake Okeechobee has three general regions that are functionally dissimilar; a littoral marsh, a nearshore region, and an open water (pelagic) region (**Figure 4**). The effects of hydrological modifications and eutrophication are related in terms of their impact on the different regions of the lake. For example, as lake stages increase, so too does horizontal mixing, or the transport of nutrient-laden sediment from the pelagic into the nearshore and littoral areas of the lake (Havens 1997, James and Havens 2005). As a result, a stage envelope was developed that is considered ecologically beneficial by maximizing the extent of littoral wetlands within the levee, while also minimizing the transport of sediment and nutrients to the nearshore and littoral regions. Conceptual Ecological Models (**Figure 5**) were developed to depict the relationships between lake stage, nutrient condition, and key floral and faunal communities that respond to or are affected by these stressors (James et al. 2006, RECOVER 2004a).

3.1 Relationship to Conceptual Ecological Models

The indicator for this performance measure is the stressor in the following conceptual ecological models:

Regional Models
Lake Okeechobee

Ecological Model for Hypothesis Clusters

Ecological Communities and Effects of Water Stages Conceptual Ecological Model

3.2 Relationship to Adaptive Assessment Hypothesis Clusters

***Ecological Premise*:** Sustained high lake levels and a reduction of spring recession conditions have resulted in the loss and degradation of historical (early 1970s) floral and faunal communities in Lake Okeechobee.

***Original CERP Hypothesis*:** This performance measure is based on the original hypothesis below, regarding stage targets in the lake. However, the cited literature (Havens 2002) actually analyzed stages from 15 ft to 12 ft (4.57 – 3.66 m), not 15.5 ft to 12.5 ft (4.72 – 3.81 m). See also Havens and Gawlik (2005).

> Providing a reduction in the frequency of extreme high water levels (stage >17 ft [5.18 m] and stage >15 ft [4.57 m] for more than 12 consecutive months) and low water levels (stage <11 ft [3.35 m] and <12 ft [3.66 m] for more than 12 consecutive months) and an increase in the frequency of spring recessions (yearly stage decline from near 15.5 ft [4.72 m] in January to near 12.5 ft [3.81 m] in June, with no reversal >0.5 ft [0.15 m]) will result in the following changes (see Havens 2002):
>
> - Increase in spatial extent of bulrush along the western lakeshore; increased spatial extent of spikerush, beakrush, willow, and other native plants in the littoral zone; and a reduction in the rate of expansion of exotic and nuisance plants.

- Increase in spatial extent of vascular submerged plants, in particular eel/tapegrass (*Vallisneria americana*), peppergrass/pondweed (*Potamogeton* spp.), and southern naiad (*Najas guadalupensis*).
- Shift in taxonomic structure of zooplankton to better support fishery resources.
- Increase in diversity, distribution, and abundance of forage fish in the littoral and nearshore zones.
- Increase in the use of the littoral zone for wading bird foraging and nesting.
- Improvement in the density, age structure, and condition of black crappie, largemouth bass, and bream in the littoral and near-shore zones.
- Reduction in the occurrence of harmful shoreline organic berms.

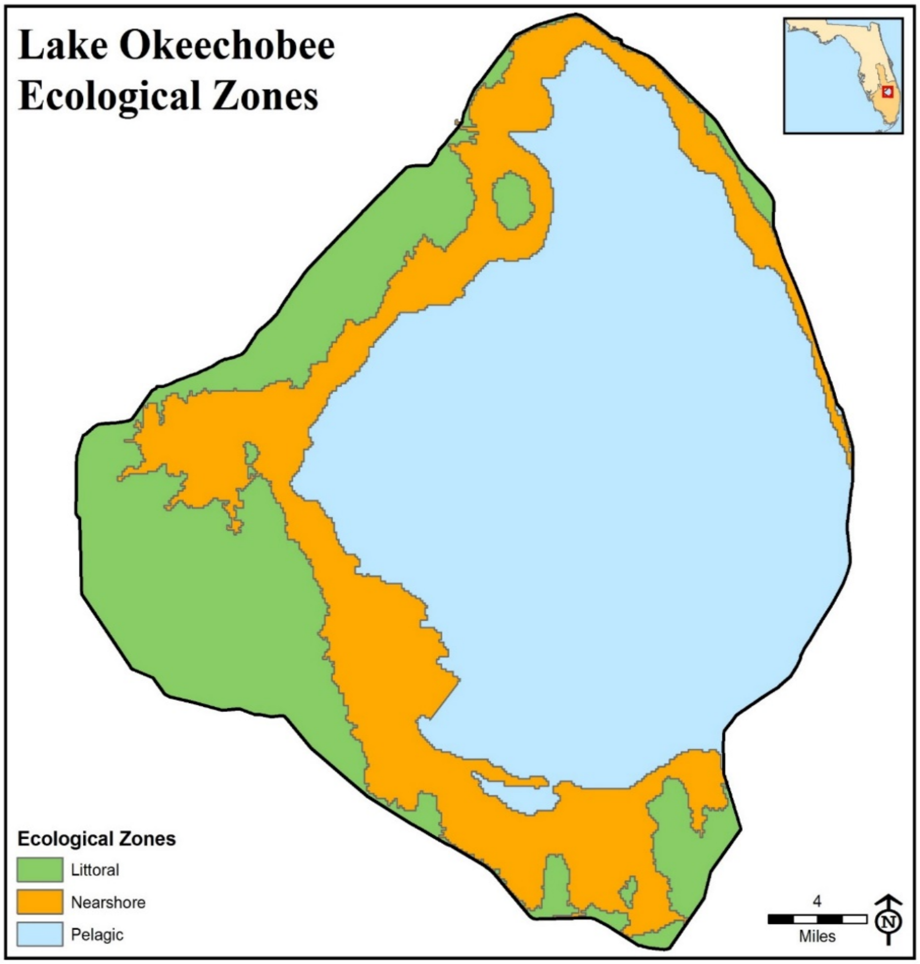

Figure 4. Lake Okeechobee ecological zones.

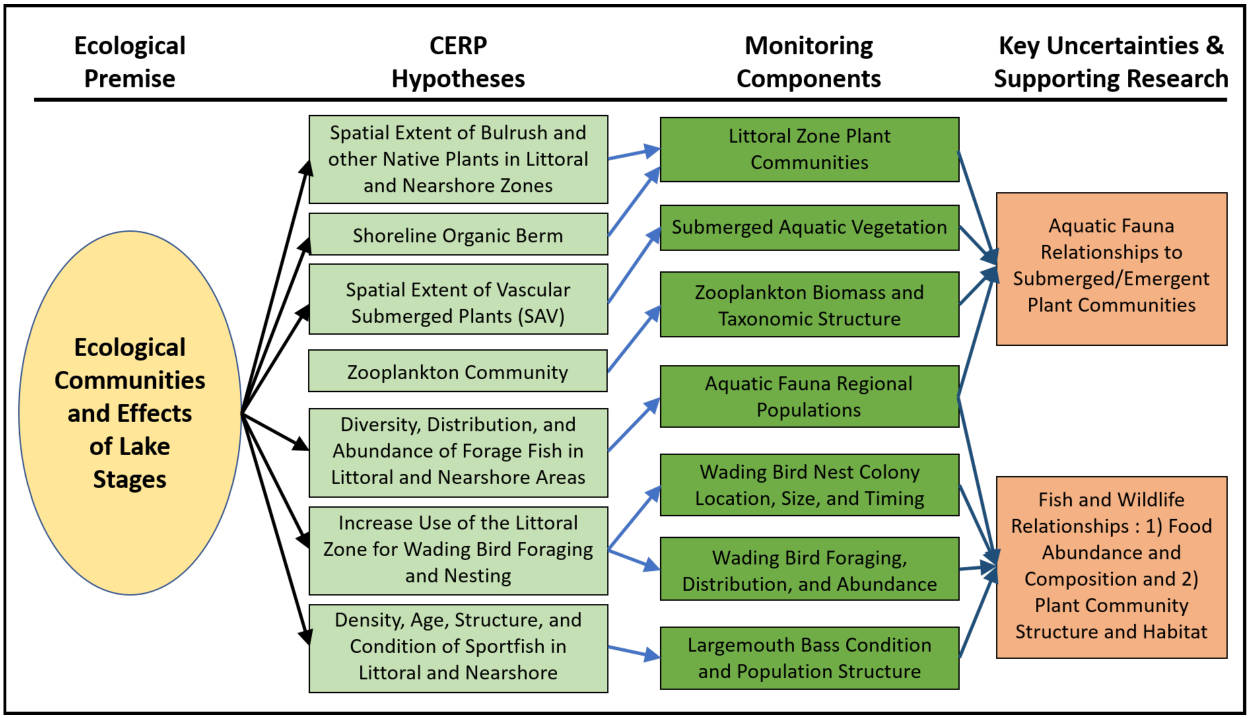

Figure 5. Conceptual framework showing relationships between ecological communities on the lake and water levels, or lake stage.

4.0 Evaluation Application

4.1 Evaluation Protocol

Evaluation is based on the 52-year (January 1, 1965 through December 31, 2016) hydrograph of lake stages that is simulated by the Regional Simulation Model-Basins (RSM-BN) model. During each day of the model run, the absolute value of the deviation (in hundredths of a foot) of lake stage from the prescribed envelope is determined and a scoring factor is applied that varies by season and distance from envelope. There are two target envelopes, one for normal years and one for recovery years following high-water events.

Scoring tallies will be done separately for stages above and below the envelope. A tally of the number of days is kept for each type of deviation, as well as the total score. For extreme high and low lake stage events, a tally is made of the total number of days that the stage is above 17 ft (5.18 m) or below 10 ft (3.05 m) NGVD. Deviations above and below the envelope are generally scored, tallied, and compared the same. While there are two target envelopes, depending on antecedent conditions, there are no targets specified for the number of years within each.

Figures 6 and **7** below illustrate how the evaluation is performed for the lake stage envelopes, where the vertical axis is stage in feet and the horizontal axis is in days of the year. The white central area (0.0 pts) is the stage envelope for Normal (**Figure 6**) and Recovery (**Figure 7**) years. The point ranges identified in each band represent the range of points from the bottom to the top of the band (for stages above the envelope, and vice versa for below). For example, a stage of 12.5 ft (3.81 m) on June 15 would have a score of 0.5, while a stage of 13 ft (3.96 m) would have a score 1.0 and 13.5 ft (4.11 m) would be 2.0. Note that penalty scores are not simply linear in all cases; going from 0.5 to 2.0 points over a 0.5 ft (0.15 m) stage difference in December, for example, but from 0.5 to 2.0 points over a 1 ft (0.30 m) stage difference in June. Similarly, the width of the beneficial envelope varies as well, with a minimum of 1 ft in winter and summer and a maximum of 2.5 ft (0.76 m) in mid-September. The Recovery envelope is similar to the Normal envelope, except that all bands are shifted down 0.5 ft most of the year; except between January to mid-May when the target envelope is shifted down 1.0 ft while the penalty bands are only shifted 0.5 ft. Most penalties are 2x the absolute deviation in feet from the envelope once a penalty of 2.0 is reached, except for the spring months below the envelope, where penalties are linear until a score of 3.0.

As an example, the hydrographs for years 2016 and 2019 are overlaid onto the envelopes. 2016 was a year that strong El Nino conditions caused substantial rainfall and inflow to the lake in the dry season, resulting in high lake stages in February (**Figure 6**). Additional rainfall events caused high stages throughout the summer and fall, and lake stages were only under 14 ft (4.27 m) for less than a month. That year would have a score of 541 for stages above the envelope and a score of 7 for stages below the envelope (548 total), and stages were only inside the envelope for 77 days. The maximum daily score was 4.65 points, which occurred on June 17 with a lake stage of 14.89 ft (4.54 m), more than 2 ft (0.61 m) above the envelope at a time of year where light penetration is critical to low elevation marsh vegetation. Note that the high stages in June and July of 2016 also would have triggered the Recovery envelope for 2017, which would shift targets and penalties downward for the following season.

Lake stages from 2019 are overlaid onto the Recovery envelope (**Figure 7**) for comparison purposes and because conditions in 2018 would have triggered a Recovery Envelope target in 2019. Water managers at the USACE did manage for lower lake stages in 2019 to aid the ecological health of the lake after impacts from Hurricane Irma in 2017 (see Welch et al. 2019). The Recovery envelope was not used as a target, of course, but 2019 stages provide an opportunity for comparison to recent management that had similar objectives as the Recovery envelope.

Stages were well below the envelope at the beginning and end of 2019 but were close for much of the middle of the year, or the peak of the growing season. 2019 would have only had a score of 13 for stages above the Recovery envelope but 228 for stages below the Recovery envelope (241 total). Stages were inside the envelope for 172 days. The maximum daily score was 2.14 points, which occurred on January 16 with a lake stage of 12.34 ft (3.76 m); over a foot below the Recovery envelope during a time of year that wading birds and snail kites rely on flooded marshes to begin the breeding season. The durations of low summer stages would have satisfied the Recovery envelope target threshold (<12 ft [3.66 m] for 112 days vs 90 day target, or <11.5 ft [3.51 m] for 83 days vs 60 day target), as would the lack of stages >16 ft (4.88 m) later in the year. If this was a modeled stage output, the target envelope would shift back to Normal the following year. Further, SAV monitoring projects demonstrated recovery of vascular SAV species along the western shorelines of the lake throughout 2019, as well as the highest *Chara* coverage since 2012 (see **Appendix A**).

While similar to the approach shown above, actual scoring of lake stages would be based on 52-year model outputs (1965 – 2016), switching between envelopes based on the specified triggers, and producing a total score relative to the envelopes; as well as a tally of exceedances and durations for stages above and below extreme highs and lows.

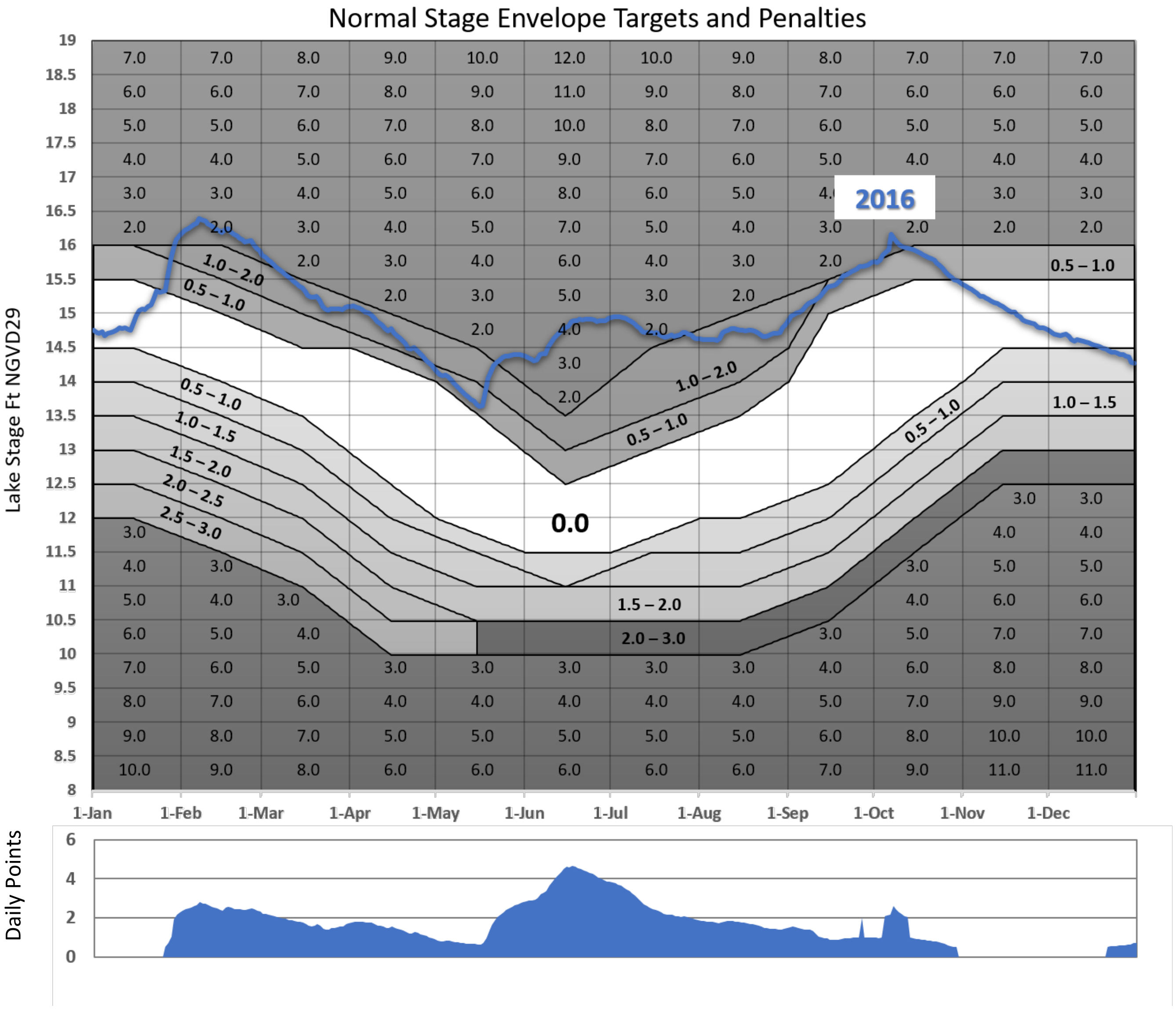

Figure 6. The Normal lake stage envelope and approximate corresponding scores that apply for lake stages outside the desired range. Scores are actually applied by the hundredths of a foot on a daily basis and may not correspond exactly to the boxes shown. For reference and as an example, 2016 stages are overlaid onto the envelope and corresponding scores are shown in the lower panel.

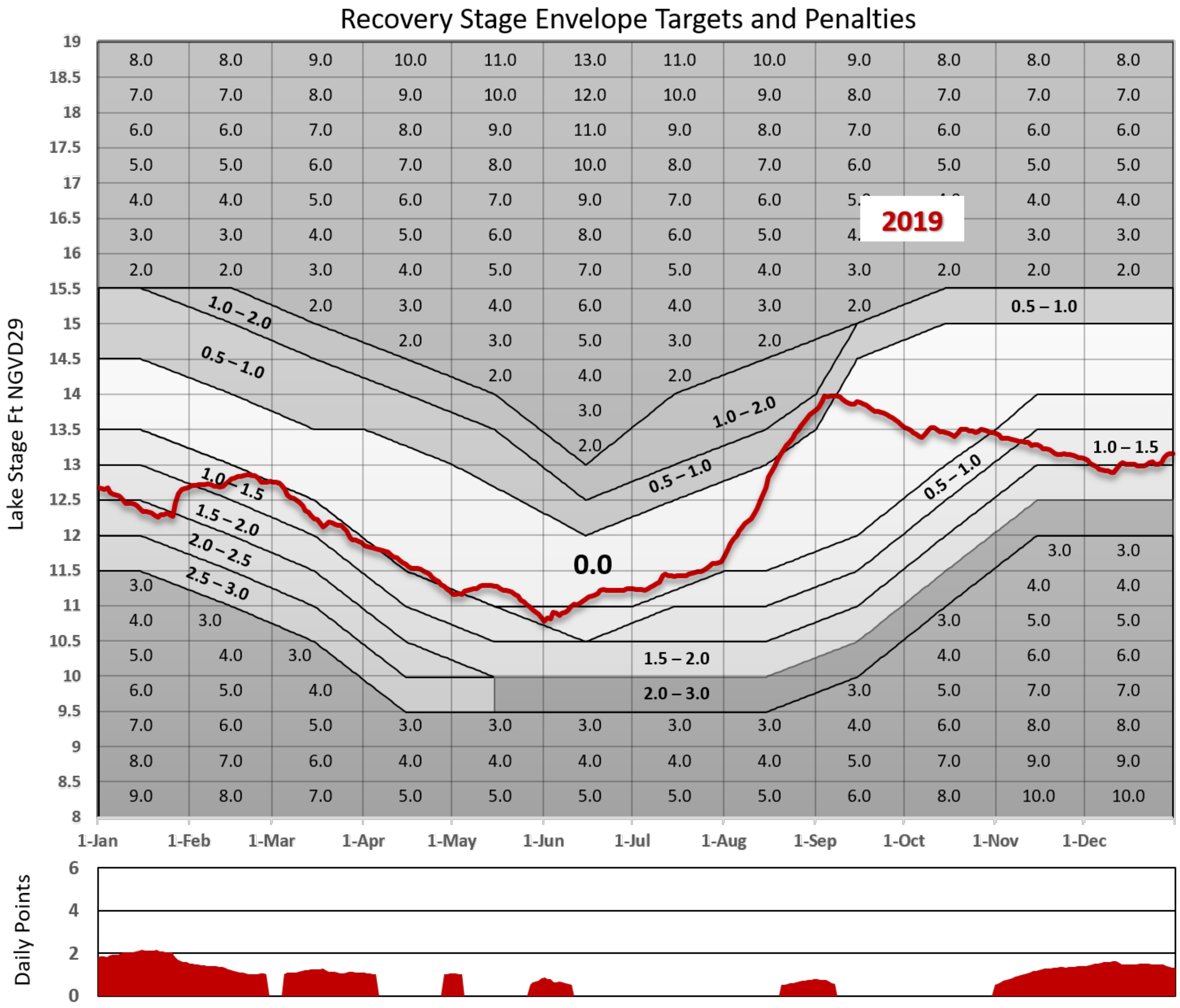

Figure 7. The Recovery lake stage envelope and approximate corresponding scores that apply for lake stages outside the desired range. Scores are actually applied by the hundredths of a foot on a daily basis and may not correspond exactly to the boxes shown. For reference and as an example, 2019 stages are overlaid onto the envelope and corresponding scores are shown in the lower panel.

4.2 Model Output

For the ecological envelope component of this performance measure, total scores should be tallied for each alternative, as well as the separate scores for exceedances above and below the envelope. The percent of time within, above, and below the envelopes should also be reported. For extreme lake stages, a histogram of the durations of events above 17 ft and below 10 ft should be displayed, as well as the total number of days for all exceedances.

4.3 Uncertainty

There is a known amount of uncertainty associated with lake stages predicted by the Regional Simulation Model-Basins (RSM-BN) (see https://www.sfwmd.gov/science-data/rsm-model for more info). There is greater uncertainty associated with the seasonal effects of lake stage on the various components of the lake's plant and animal community. Stage is an indicator of water depths in the marsh and nearshore zones. Therefore, stage also indicates the resulting degrees of physical, chemical, and biological effects. For example, at stages of 17 ft (5.18 m) (or greater than) sediments and associated nutrients can be transported by wind and wave action into the interior marsh, where long-term degradation can occur (Havens 2002). This transport can occur until the lake drops below 15 feet (Jin et al. 2000). There is little uncertainty about these physical effects of stage under normal conditions, but there is more uncertainty with severe events like hurricanes; which increase sediment resuspension and transport. Additionally, while there are established linkages between stressors and attributes within the lake (Havens 2002, Havens and Gawlik 2005), there is some uncertainty about the magnitude of the biological response. For example, sportfish benefit from healthy SAV communities, but other factors affecting prey, survival, and reproduction over a several year timeframe complicates and obscures population response to stages that benefit SAV. Similarly, wading birds benefit from lake stages near the top of the envelope (or higher), but need lower stages to improve nesting substrate availability and foraging habitat structure; return frequencies are not addressed with these envelopes and there is uncertainty regarding the best balance of lower and higher stages.

Therefore, while the envelope appears very specific in terms of stage requirements throughout the year, the shape reflects a broad literature review and the best professional judgment of working group members based on monthly stage targets. Average monthly values were converted to daily stages using linear interpolations, and the uncertainty around specific stage targets is captured in the scoring method; points increase with divergence from the envelope and may vary at times of year where specific targets are deemed important. The varying width of the envelope and the varying penalty scores together account for some of the uncertainty in stage targets. It is not possible to address all the uncertainties associated with all the physical-chemical-biological processes in Lake Okeechobee; however, the information provided here is based on decades of research in the ecosystem and improves upon the previous version of the stage envelope.

5.0 Monitoring and Assessment Approach

5.1 MAP Module and Section

Hydrology Monitoring Network Module section 3.5.3.1 (RECOVER 2004b). Daily lake stages are calculated by the USACE using four interior lake stations (L001, L005, L006 and LZ40) and four perimeter stations (S-308, S-352, S-4 and S-133), which are maintained by the South Florida

Water Management District. Assessment is performed by tracking changes in lake stage relative to the envelopes described above. Additional assessment is performed by identifying the frequency of occurrence and duration of events where stage rises above 17 ft or falls below 10 ft NGVD. Further, results from long-term monitoring of a variety of environmental parameters (see below) is used to assess and validate lake health, and to inform this performance measure. See *The RECOVER Teams' Recommendations for Interim Goals and Interim Targets for the Comprehensive Everglades Restoration Plan* – Indicator 2.2 Water Levels in Lake Okeechobee (RECOVER 2005)

5.2 Assessment Approach

Long-term monitoring of the status of Lake Okeechobee health is generally related to (1) phosphorus levels, (2) nutrient and phytoplankton dynamics, (3) submerged aquatic vegetation, (4) emergent plants, and (5) wildlife. Conceptual ecological models were developed to address how hydrologic and nutrient issues affect these attributes, and those efforts were used to select indicators of the overall ecological condition of the lake. These indicators are representative of the three sub-regions in the lake (marsh, nearshore, and pelagic) and are affected by changes related to lake stage, i.e. the relationship between stage and horizontal mixing of nutrient laden sediments. They include a variety of water quality indicators, including; total phosphorus concentration and load, chlorophyll *a*, phytoplankton (diatom and cyanobacteria ratios), and water clarity; and also, submerged and emergent vegetation communities, including minimal coverages of exotic plants; important recreational sportfish species black crappie (*Pomoxis nigromaculatus*) and largemouth bass (*Micropterus salmoides*); and wading birds and snail kites.

Monitoring programs through the South Florida Water Management District, Florida Fish and Wildlife Conservation Commission, US Army Corps of Engineers, US Geological Survey and others provide assessments of indicator health, as well as verification of their relationships to lake stage. Together these programs have provided decades of assessment data and will continue to inform the efficacy of performance measures like the one described in this document. Data from these programs form the basis of this current update and will be used to evaluate and validate this performance measure in the future.

6.0 Future Tool Development Needed to Support Performance Measure

6.1 Evaluation Tools Needed

RSM-BN outputs, daily scores for the lake stage envelope, and exceedance counts, durations, and return frequencies of extreme (>17ft or <10ft) events.

6.2 Assessment Tools Needed

Daily average lake stage information from the composite USACE station. As of this writing, the average is comprised of four interior lake stations (L001, L005, L006 and LZ40) and four perimeter stations (S-308, S-352, S-4 and S-133) to account for daily variations in stage due to wind seiche.

7.0 Notes

This Performance Measure supersedes and addresses LO-3 Lake Okeechobee Stage Envelope (Last Date Revised: Mar 7, 2007). The extreme lake stage performance measure targets are unchanged but there are slight modifications to their scoring methodology. Earlier versions used relativized scoring methods in order to calculate habitat units, which is not always a part of evaluations. Both the earlier and current versions use counts and durations of extreme stage exceedances, which can be relativized as needed for individual project evaluations.

The original Lake Okeechobee Stage Envelope performance measure was modified in several ways;

- Adjusted approximately 0.5 ft lower to align with originally cited research (Havens 2002) that specified 12 ft and 15 ft as low and high targets, rather than 12.5 ft and 15.5 ft. It is unclear why the earlier version used higher stage targets than those referenced in the study that was cited as support of the targets.
- Adjusted width of envelope to allow greater flexibility in spring and fall due to importance of inter-annual variability, and reduced flexibility for low-stage target to reflect critical nature of low stage for SAV and other communities.
- Modified scoring methodology to reflect a softer buffer around stage targets at certain times of year and harder buffers where stage targets were deemed critical. Also increased scores farther outside of the envelope to attain more variation when scoring alternative model outputs.
- A relativized scoring system (0-100) to calculate habitat units is not provided, but could be applied as needed in future evaluations.

8.0 Working Group Members

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10.0 Appendix A. Submerged Vegetation and Lake Stage

Submerged aquatic vegetation (SAV) in Lake Okeechobee serves as an indicator of aquatic ecosystem health and is important for overall lake ecology as it provides habitat for fish, macroinvertebrates, zooplankton and other aquatic taxa; stabilizes sediments, and improves water quality through nutrient uptake and wave attenuation. While structurally complex, robust SAV communities comprised of vascular species (e.g. *Vallisneria americana, Potamogeton illinoensis, Hydrilla verticillata*) typically represent better habitat than ephemeral macroalgae, the latter is an excellent indicator of growing conditions on Lake Okeechobee. Musk grass (*Chara* spp.) is often the first to benefit from higher light penetration associated with lower lake stages (Havens et al. 2001) and its coverage can vary by many thousands of acres from year to year, depending on conditions. We focused on this macroalgae as a representative of light penetration for SAV, benthic algae, epiphytic algae, or emergent plants at lower elevations.

Chara coverage on the lake has been estimated from as little as zero to nearly 30,000 acres (12,000 ha) during the 2001 – 2019 period of monitoring record (**Figure A-1**), and it occurs primarily in the south and southwest portions of the lake on peat or sandy-peat soils (Havens et al. 2002). These estimates of coverage are negatively correlated with summer lake stage (**Figure A-2** and **Figure A-3).** Summer months, specified here as June and July, tend to have less wind (lower turbidity), lower lake stage, and a long photoperiod. Variation in the annual coverage of *Chara* is better explained by minimum summer lake stages than maximum winter lake stage, likely due to its ephemeral nature. Using a recursive partition tree (JMP 14), the 30-day minimum lake stage during June and July (lowest elevation exposed for at least 30 days) was a better predictor of *Chara* coverage than absolute minimum stage, or the 60 and 90 day minimum stages. In fact, a single stage threshold of 13 ft (3.96 m [30d Jun/Jul min]) explained 71% of the variation in *Chara* coverage in the dataset.

Similarly, a plot of *Chara* and lake stages shows a sigmoidal relationship ($R^2 = 0.79$) to the June/July 30-day minimum lake stage **(Figure A-2),** especially when excluding years where coverage was affected by high turbidity following hurricanes (2005, 2006, 2018). There are stark differences in *Chara* coverage between low and high summer lake stages, but between June/July 30-day minimums of roughly 12-13 ft (3.66-3.96 m) there is wide variation (less of a relationship to stage) in coverage values. Antecedent conditions may explain this variation, as most years with higher *Chara* coverage were preceded by years with low summer stages (2002, 2009, and 2012) while years with lower coverage were preceded by years with higher summer stages (2014 and 2017). **Figure A-3** shows daily lake stages for years with the highest and lowest *Chara* coverages. These analyses demonstrate how poor growing conditions are for SAV communities when summer lake stages are high (30-day mins >13 ft [3.96 m]), and how important low lake stages are for their recovery (see also Havens et al. 2004). Detailed research results regarding high stage impacts on the lake's plant and animal communities can be found in Maceina and Soballe (1990), Havens (1997), and Havens et al. (1999, 2001).

Vascular species on Lake Okeechobee tend to occur more along the western shorelines of the lake in areas with less peat substrate and with steeper shoreline slopes (Havens et al. 2002). While most of the peak coverages in vascular SAV have been documented 1-2 years following low lake stages, these estimates are from a spatially dispersed, lake-wide monitoring program that is not designed to capture small-scale or localized fluctuations. After Hurricane Irma and subsequent turbid, high lake stages in the summer of 2018, SAV coverage was at the lowest point on the lake since prior hurricanes in 2004-2005 (Zhang et al. 2020). The vascular SAV community consisted almost entirely of palustrine-type species (coontail [*Ceratophyllum demersum*] and bladderwort [*Utricularia* spp.]) that were found behind or within emergent plant communities which were less affected by the winds and waves associated with the hurricane. Nearly all the nearshore zone outside of dense emergent vegetation was devoid of SAV, presumably from high wind/wave energy and subsequent turbid water.

In order to document SAV response, transects were established along elevation gradients from the edge of dense emergent vegetation (roughly 12 ft [3.66 m] in elevation) to outside of the emergent littoral zone (<9 ft [2.74 m] in elevation), with samples occurring approximately every 6 in (15 cm) in elevation change (**Figure A-4**). SAV wet-weight biomass and average stem heights were measured from approximate 1 m^2 samples twice annually from 2018-2019, in the spring and late summer/fall period.

Sampling in 2018 found almost no SAV, either in the spring or fall samples. Beginning in early 2019, SAV regrowth was observed in the shallowest areas, and by the fall of 2019 widespread coverage of vascular SAV communities was observed up and down the western shorelines (FWC, pers. comm.). Sampling showed stem heights exceeding 3 ft (1 m) in dense *Vallisneria* beds, with peak biomasses and heights occurring at elevations close to 11 ft (3.35 m), or roughly the elevation of the lowest summer water levels (**Figure A-5**). Little to no regrowth was observed at elevations of approximately 9 ft (2.74 m), which had minimum depths of nearly 2 feet (0.61 m) during the summer.

Lake stages in 2019 were much lower than even the proposed Recovery envelope (**Figure 7**) in the beginning and end of the year but were generally within the lower portion of the envelope in the spring and summer growing period. Despite growing conditions remaining optimal for longer than would occur in the Recovery envelope, no significant regrowth of SAV was observed in Fisheating Bay; an area of extensive, dense communities of *Vallisneria* and *Hydrilla* in normal years. Dark stained water from Fisheating Creek may have limited regrowth in this area, demonstrating that even lower stages than occurred in 2019 may be necessary to recoup SAV in some areas of the lake after major hurricanes. However, hurricanes like Irma are generally rare events, and the Recovery envelope is designed as a balance between low stages for SAV regrowth while maintaining some level of marsh inundation and habitat availability for fish and wildlife communities dependent on the lake. Therefore, we established thresholds for a return to Normal envelope targets based on the vigorous regrowth observed along the outside of the western marsh, and not what would likely be required for similar recovery in Fisheating Bay. Low stage thresholds were further defined as to coincide with the transition between dry and wet seasons, which is typically when the lowest stages occur on the lake.

In 2019, stages were below 12 ft (3.66 m) for 112 days between Apr 15 and Sep 15 and were below 11.5 ft (3.51 m) for 83 days between May 1 and Aug 1. Further, lake-wide SAV sampling showed dramatic increases in *Chara* coverage, as well as moderate increases in vascular SAV as early August 2019 (**Figure A-6**). Based on these positive results, stages were considered low enough for long enough to return to the Normal envelope, if:

- Lake stages are below 12 ft (3.66 m) for 90 days between Apr 15 and Sep 15

OR

- Stages are below 11.5 ft (3.51 m) for 60 days between May 1 and Aug 1

Continued monitoring of SAV and other ecological indicators on the lake will enable refinements to this and other ecological performance measures in the future, as needed.

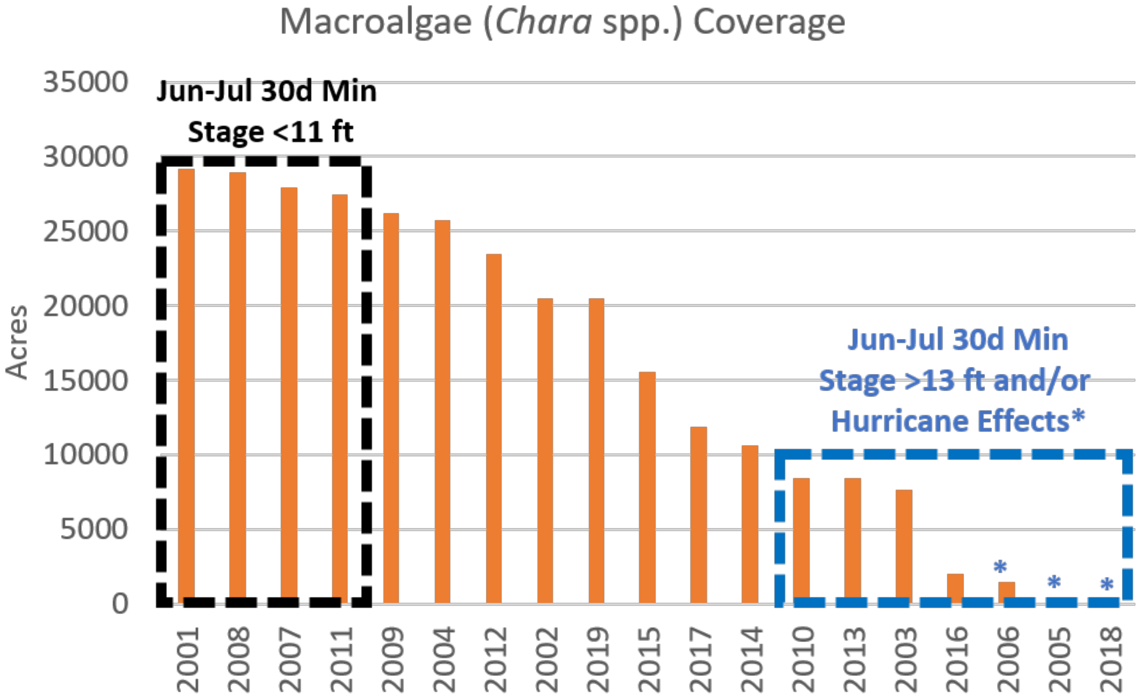

Figure A-1. Estimated maximum annual coverage (2001-2019) of *Chara* in descending order. Black dashed box represents low stage years in Figures A-2 and A-3 and blue dashed box represents high stage years in **Figures A-2** and **A-3**. Note that 2006 and 2018 did not have high summer stages but had extremely turbid water due to hurricanes the year prior.

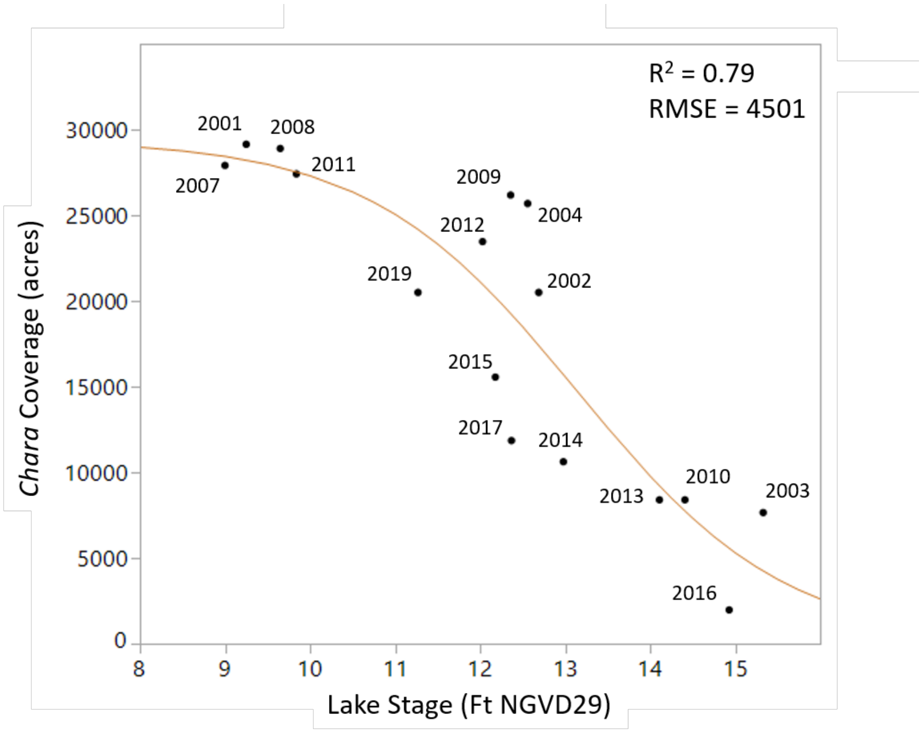

Figure A-2. A sigmoidal curve fit to estimated *Chara* coverage relative to the 30-day minimum stage from June through July. Years 2005, 2006 and 2018 were excluded due to hurricane effects on turbidity.

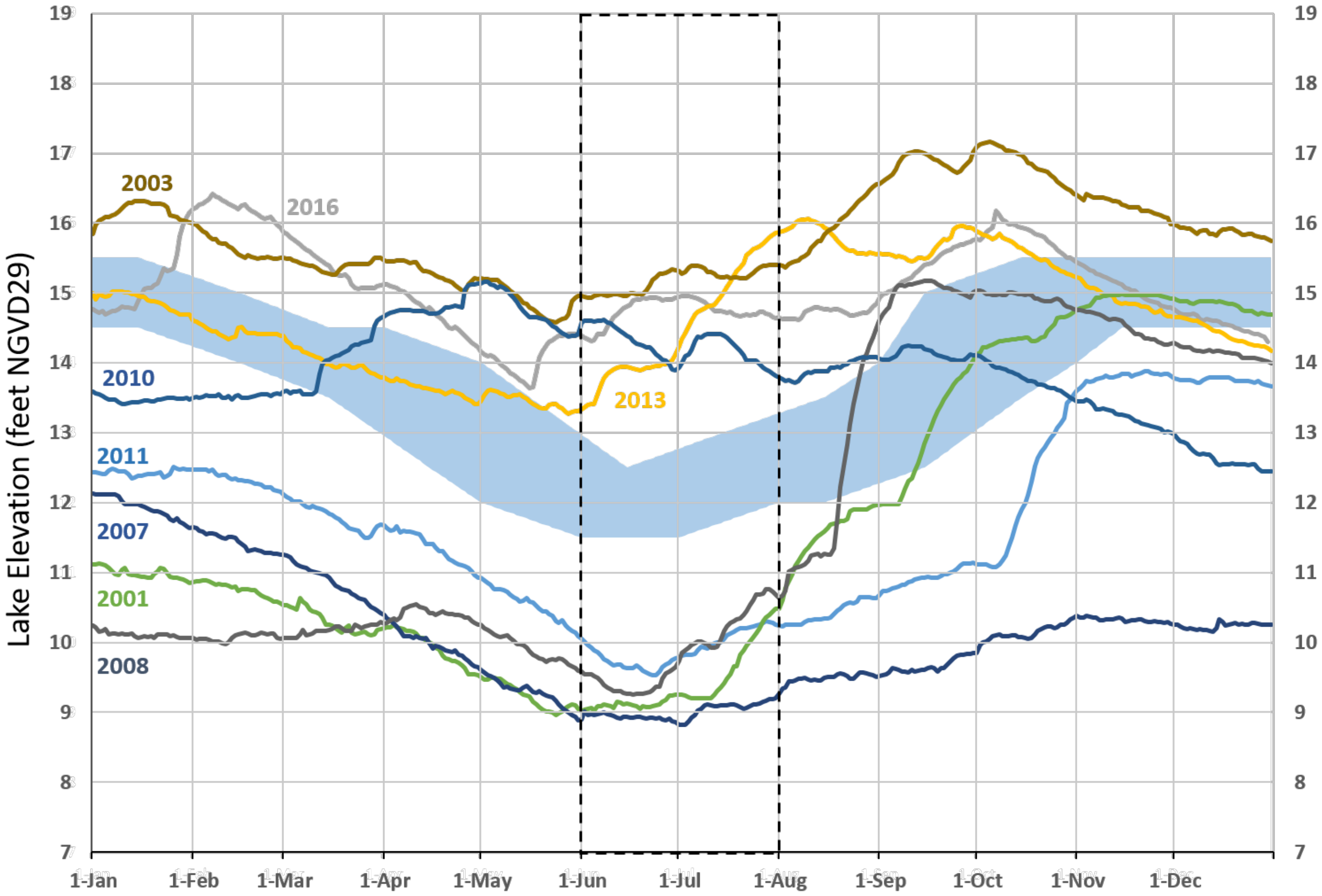

Figure A-3. Years with high and low lake stages in the summer that correspond to extremes in *Chara* coverage estimates in **Figure A-1**. The dashed box highlights the June-July period analyzed in Figure A-2 while the blue shaded area represents the proposed Ecological Envelope under normal conditions.

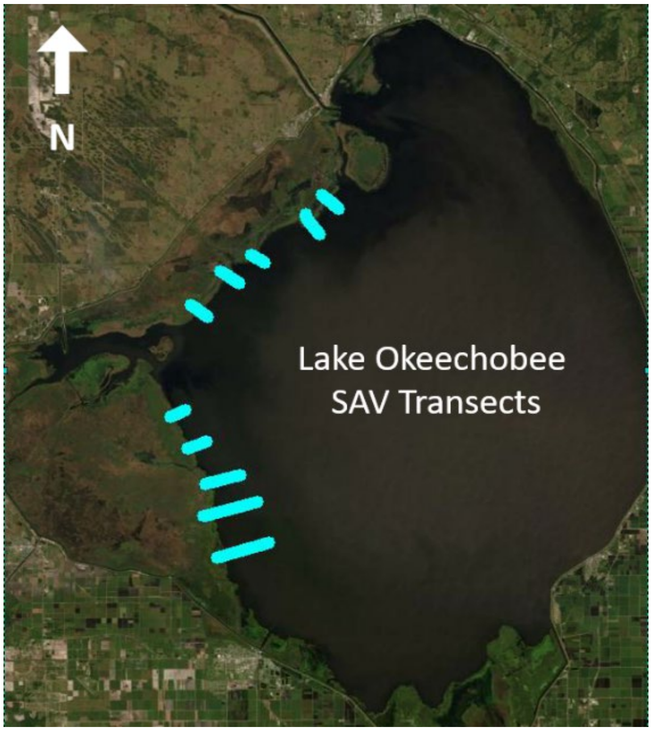

Figure A-4. Location of SAV monitoring transects established in 2018 that were used in **Figure A-5**.

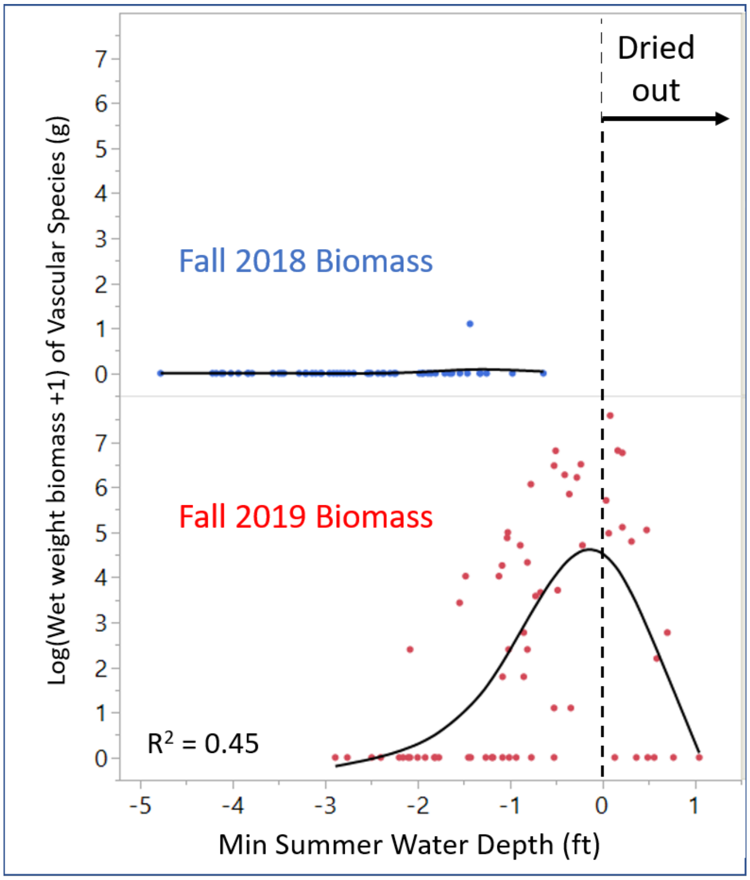

Figure A-5. Biomass of wet weight, vascular SAV (log[x +1]) in grams from SAV monitoring transects shown in **Figure A-4**. The dashed line represents the approximate elevation that was exposed at minimum summer lake stage. Smoothing spline (lambda 0.2) is fit to data for visual purposes.

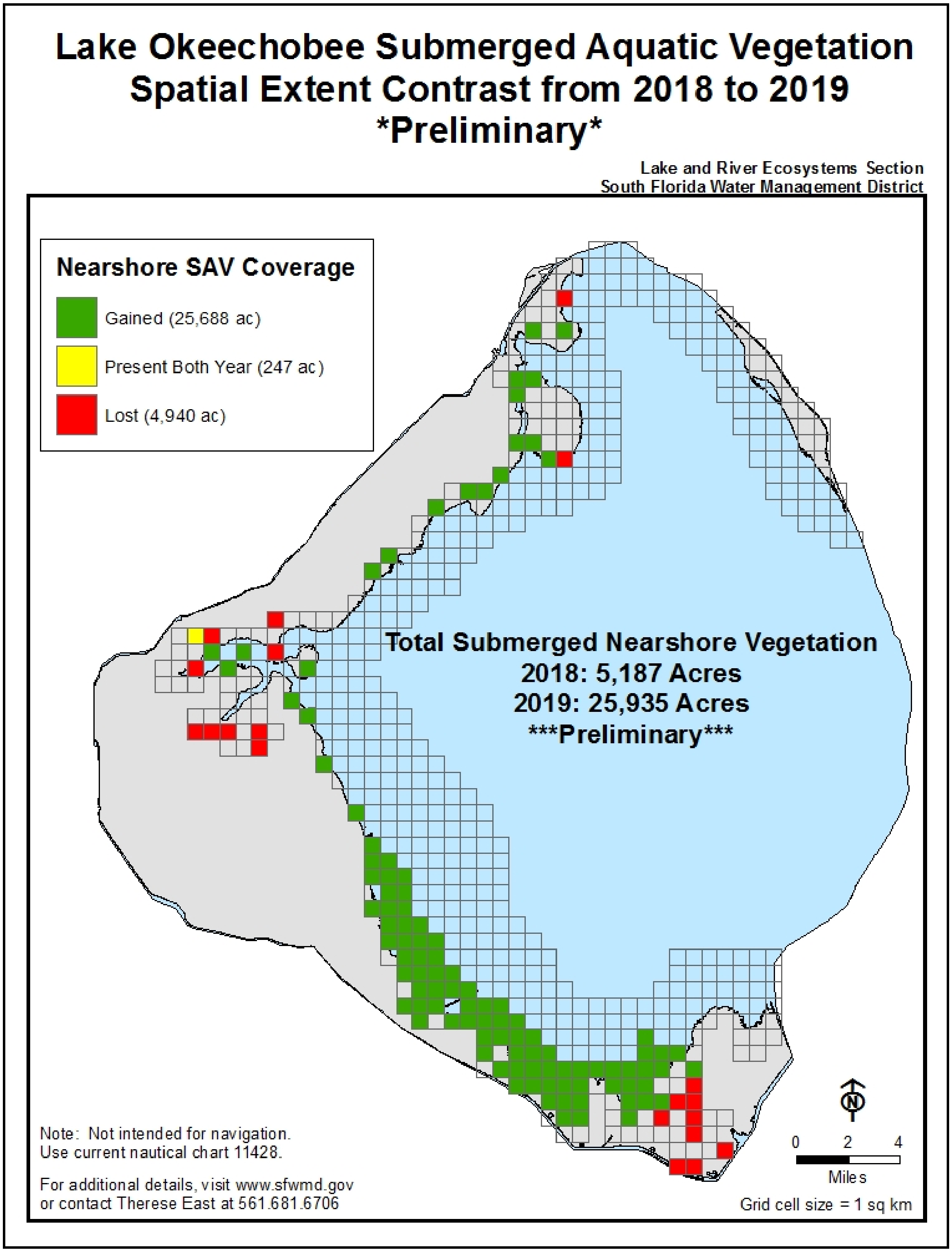

Figure A-6. Location of monitoring grids where SAV was gained (green), lost (red), or maintained (yellow) between August of 2018 – August 2019.

Attachment G-2: Northern Estuary Performance Measures

RECOVER Northern Estuaries Performance Measure: Salinity Envelope

Date Revised: July 2020
Acceptance Status: Approved July 7, 2020
Type of Performance Measure: Evaluation

ABSTRACT

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

The Restoration, Coordination, Verification (RECOVER) Northern Estuaries program monitors long-term trends of several ecological indicator species ("indicator species") and will assess CERP impacts as projects come online. These species include the Eastern oyster (*Crassostrea virginica*), and the freshwater/oligohaline submerged aquatic vegetation (SAV) species tape grass (*Vallisneria americana*) and the marine SAV species shoal grass (*Halodule wrightii*). Data from experimental and field-based studies on organism responses to changes in salinity, information from peer-reviewed and gray literature, and long-term monitoring data were used to set salinity ranges around conditions of optimum, stressful, and damaging effects for each indicator species. The CH3D hydrodynamic model used the daily historical flow data from a 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.

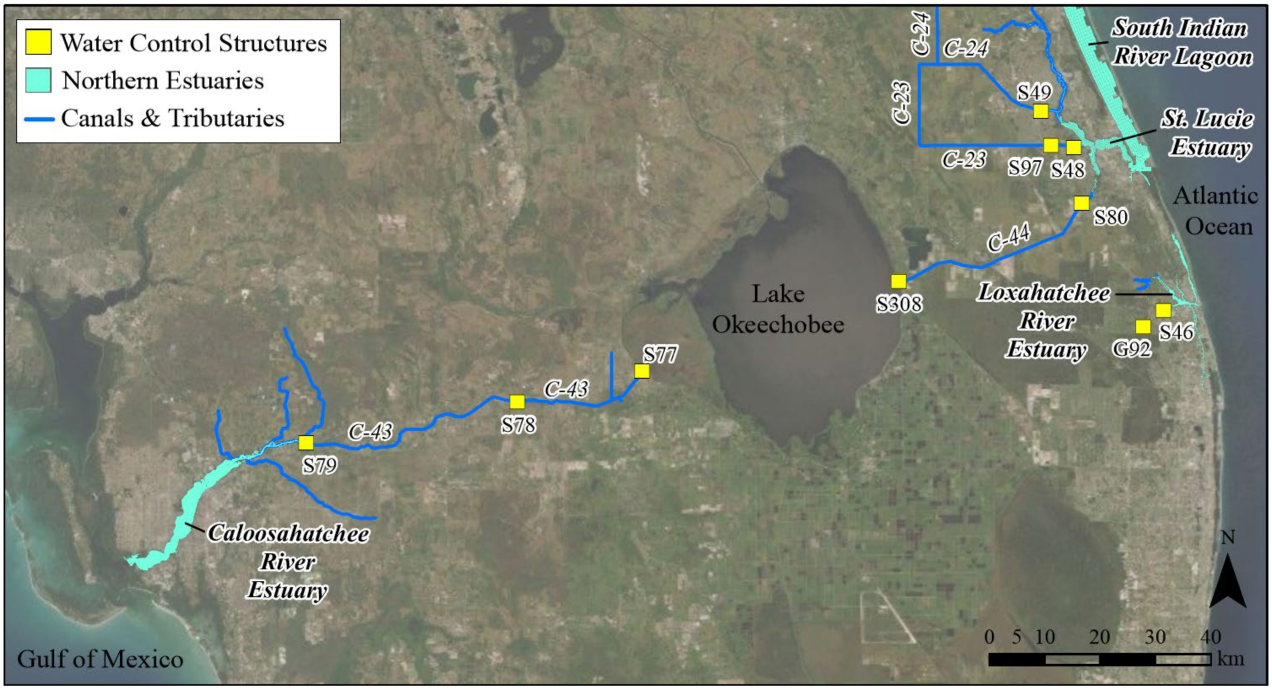

***Figure 1**. The Caloosahatchee, St. Lucie, and Loxahatchee Estuaries relative to Lake Okeechobee and the greater Everglades ecosystem*

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.

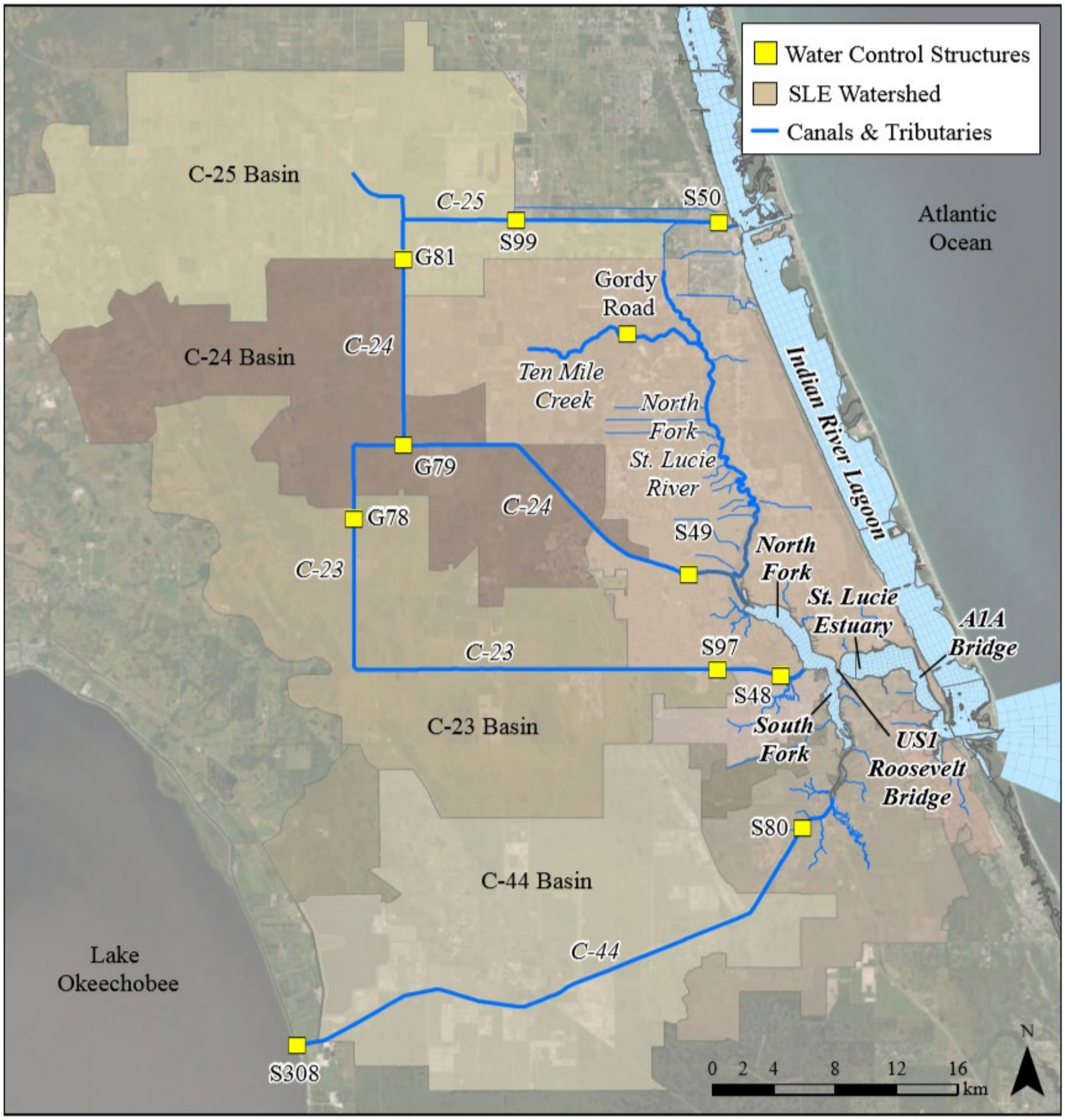

***Figure 2**. The St. Lucie Estuary relative to proximity to major waterbodies and sources of inflow*

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.

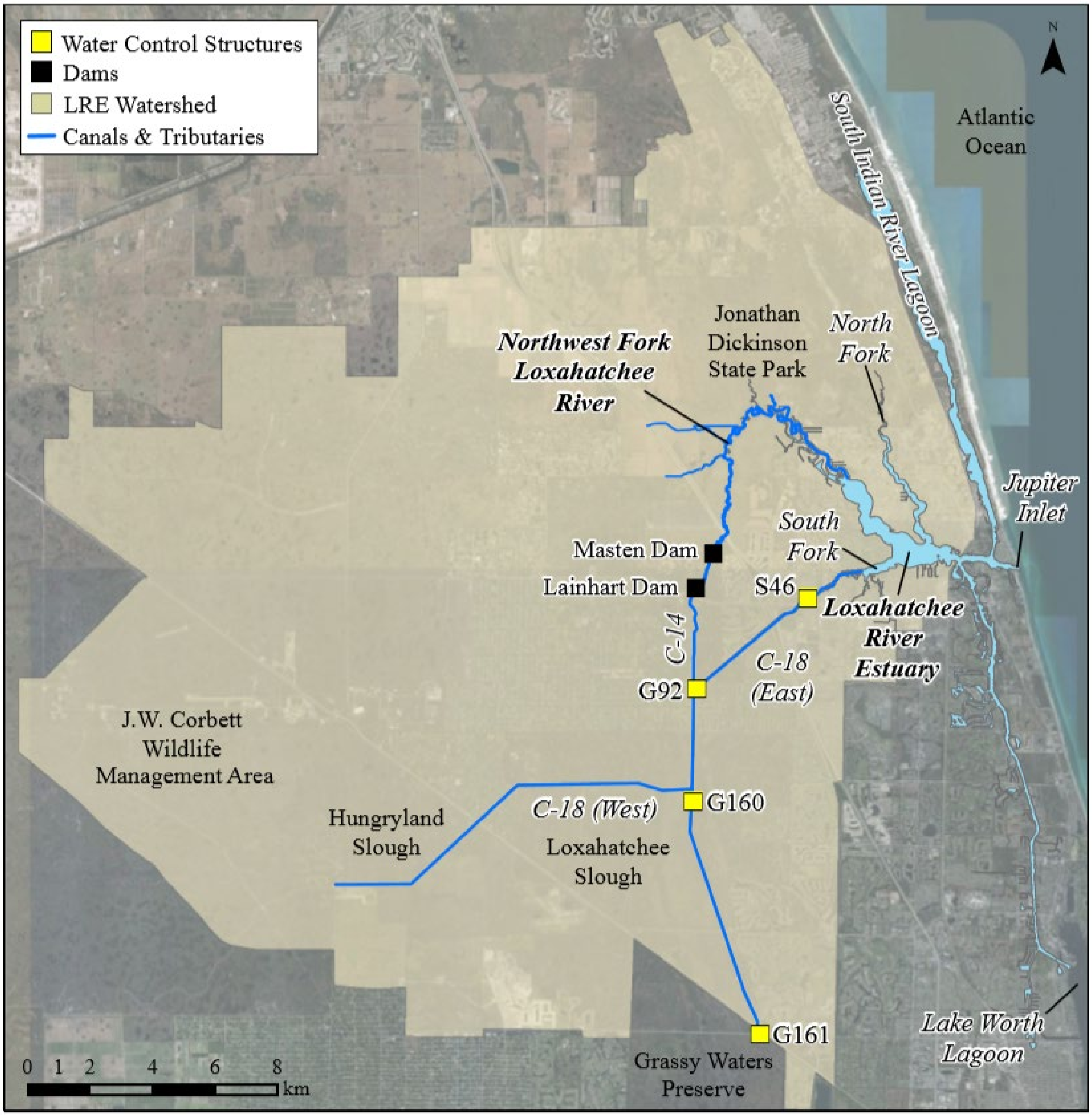

Figure 3. *The LRE and major tributaries including the Northwest Fork*

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).

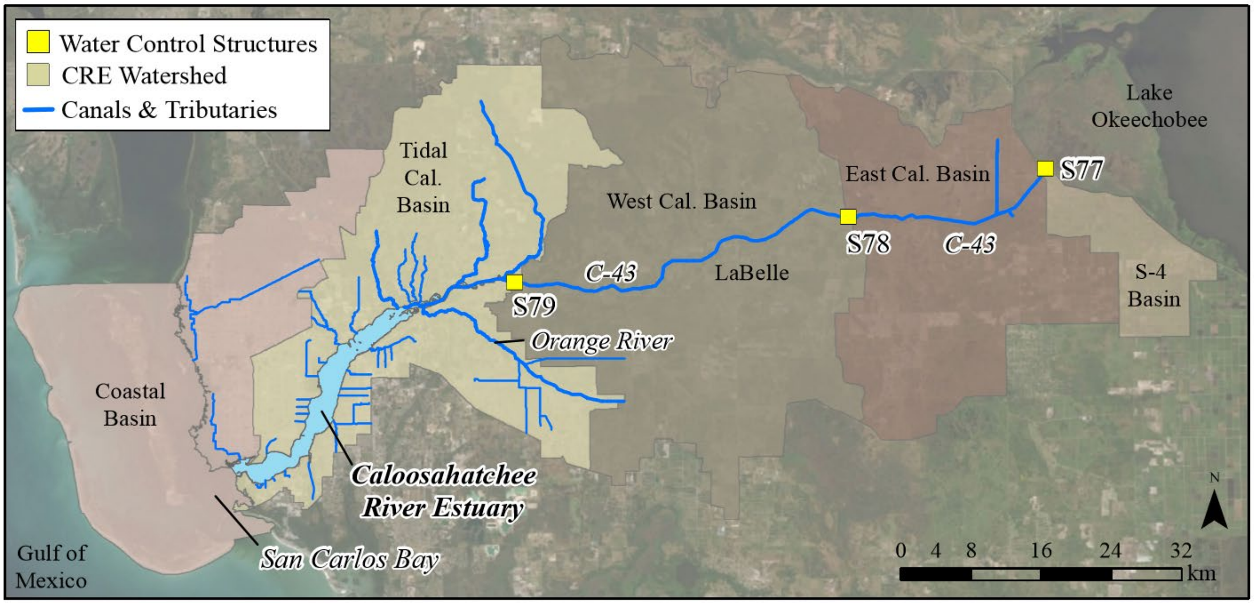

***Figure 4**. The CRE relative to its proximity to major waterbodies and sources of inflow*

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).*

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

2.3 Eastern Oyster

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

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

At salinities >20, marine predators and pests (e.g., oyster drills, boring sponges, crabs, and fish such as black drum) can infiltrate oyster reefs (Gunter 1955; Brown 2008; Barnes 2010; Carroll 2015; Kimbro 2017). A field study comparing oyster populations in Ochlockonee and Apalachicola Bays in north Florida, two estuarine systems that exhibit similar rainfall but 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	Targets
	(2100–2600 cfs) and Damaging Flow Envelope (>2600 cfs)	
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.

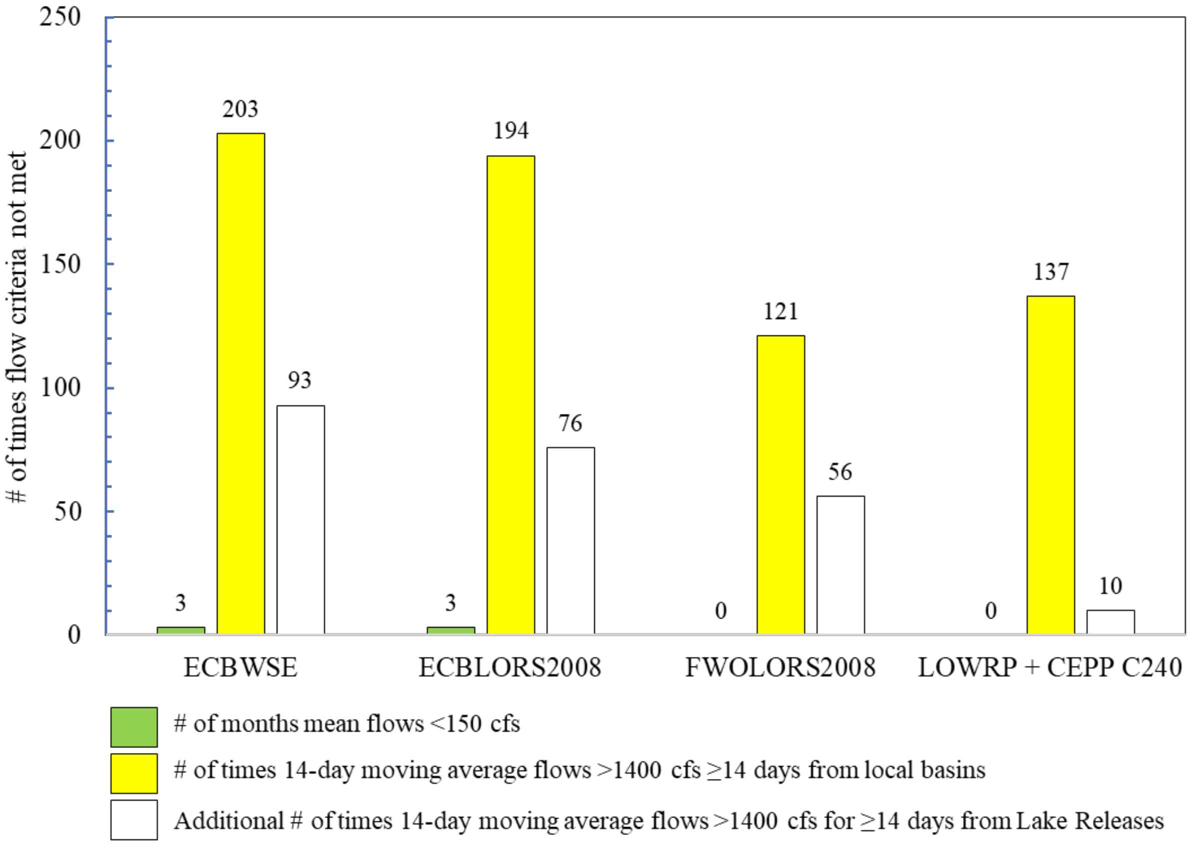

***Figure 5**. Number of times the 14-day moving average or monthly flows to the SLE fell below the Optimum Flow Envelope of 150–1400 cfs between the four condition simulations, over the period of record (1965–2005).*

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).

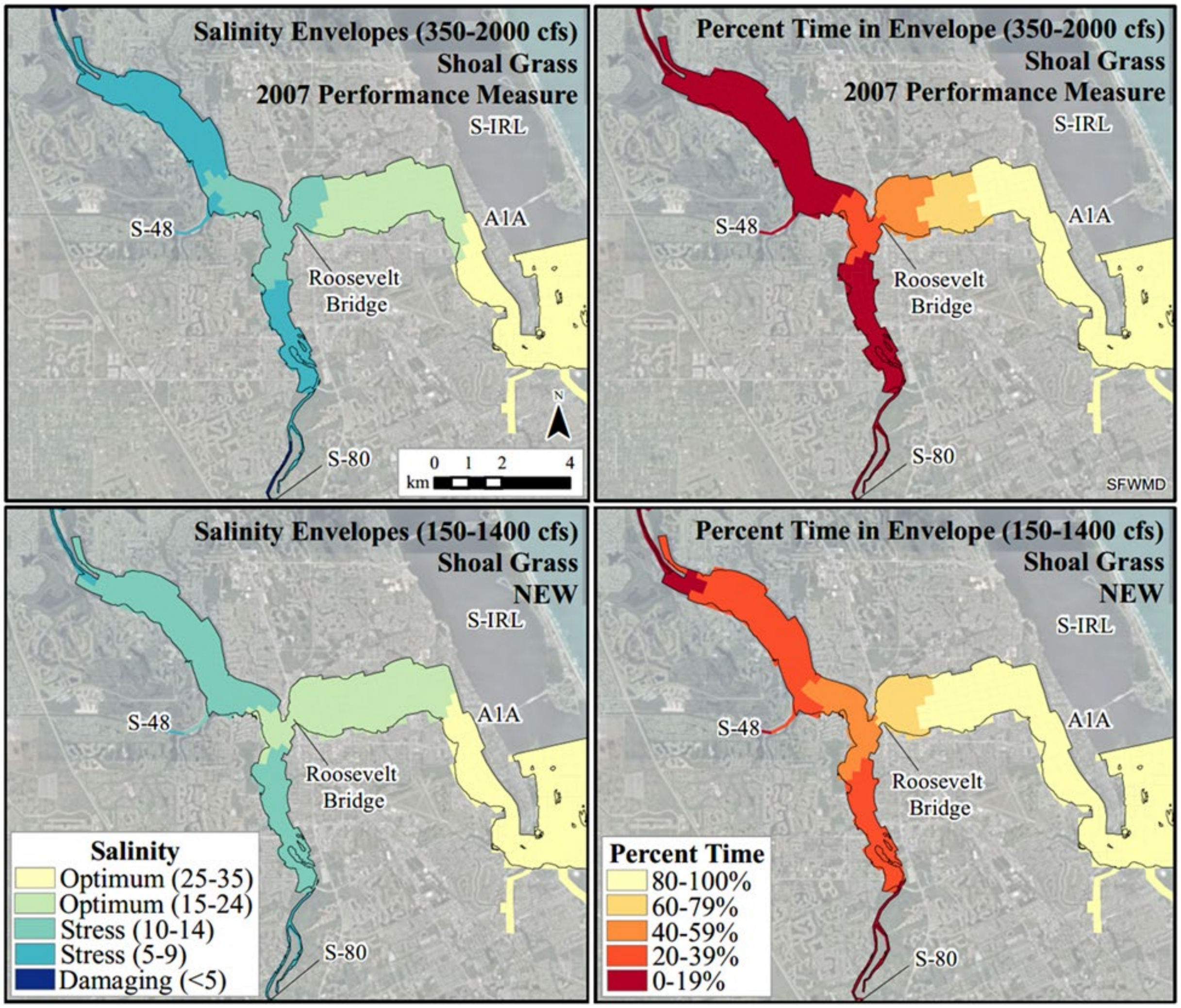

***Figure 6**. Mean salinity and percent time within Optimum Salinity Envelope for shoal grass (salinities 15–45) in the SLE modeled on target flows from the 2007 PM (350–2000 cfs) and the new, revised PM (150–1400 cfs). With the new, revised flow target, salinity conditions improve to optimum throughout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

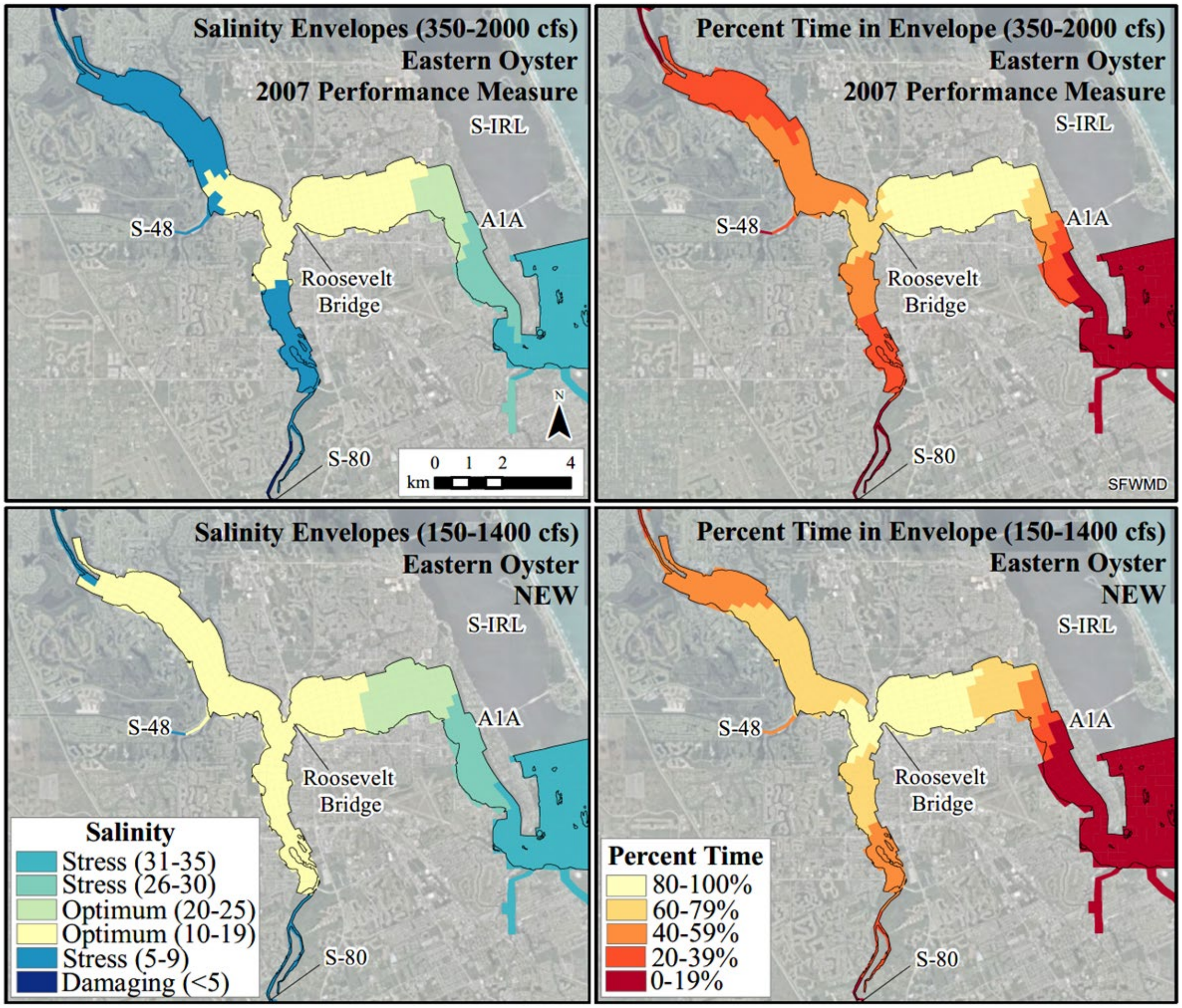

***Figure** 7. Mean salinity and percent time within Optimum Salinity Envelope for Eastern oyster (salinities 10–25) in the SLE modeled on target flows from the 2007 PM (350–2000 cfs) and the new, revised PM (150–1400 cfs). With the revised flow target, salinity conditions improve to optimum throughout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

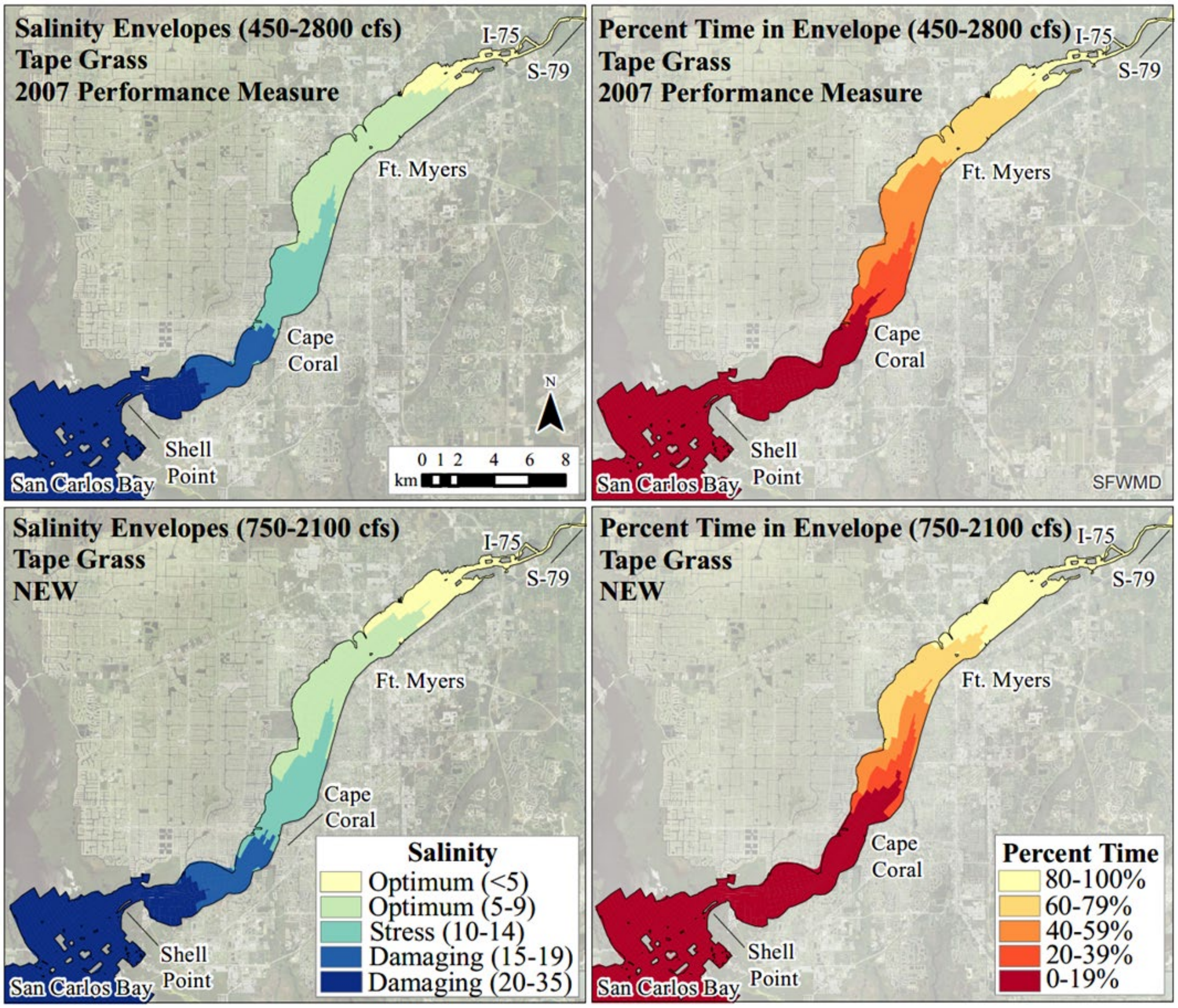

***Figure 8**. Mean salinity and percent time within Optimum Salinity Envelope for tape grass (salinities <10) in the Caloosahatchee River Estuary modeled on target flows from the 2007 PM (450–2800 cfs) and the new, revised PM (750–2100 cfs). With the revised flow target, salinity in the range of 0–5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

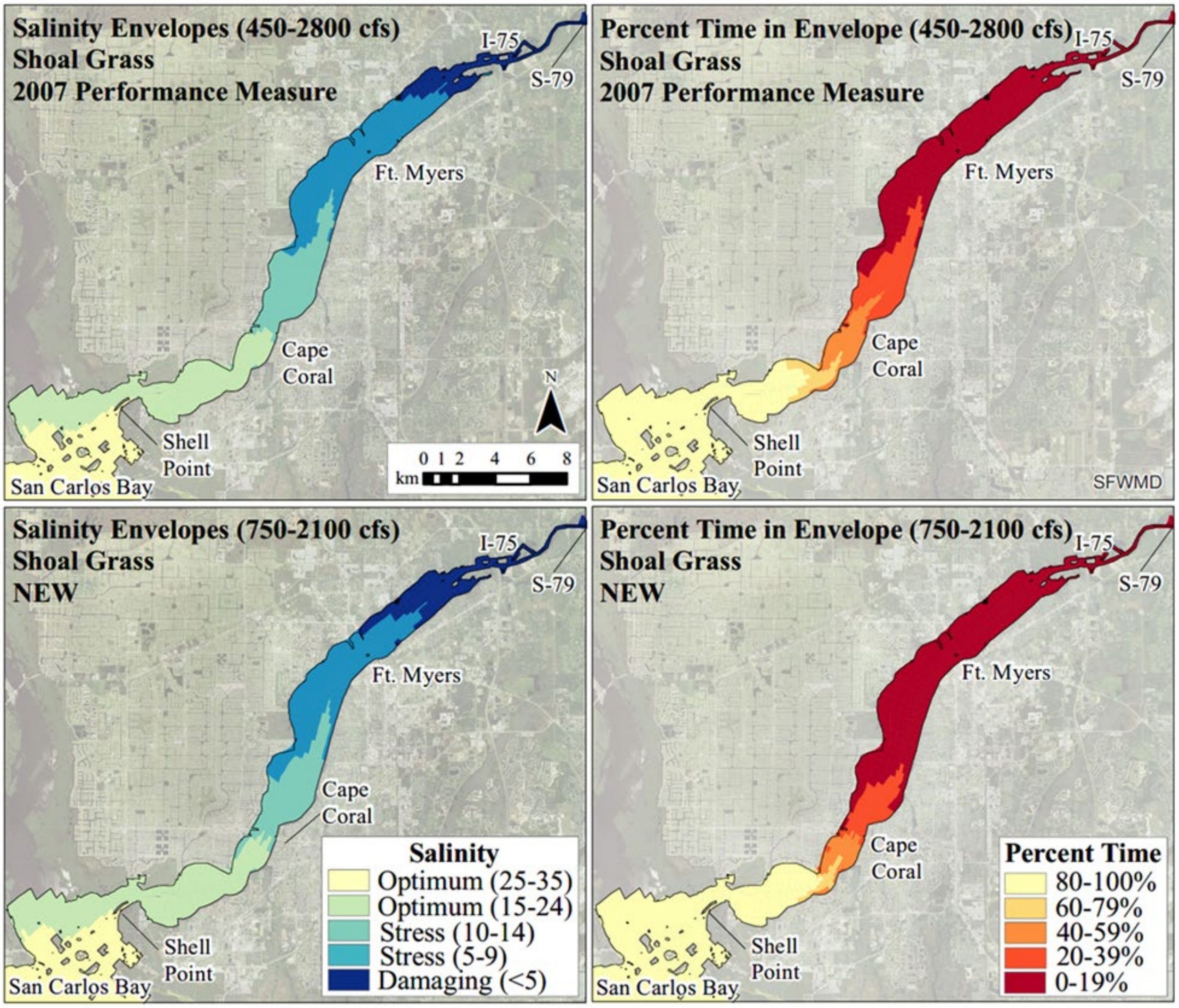

Figure 9. *Mean salinity and percent time within Optimum Salinity Envelope for shoal grass (salinities 15–45) in the Caloosahatchee River Estuary modeled on target flows from the 2007 PM (450–2800 cfs) and the new, revised PM (750–2100 cfs). With the revised flow target, percent time within Optimum Salinity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

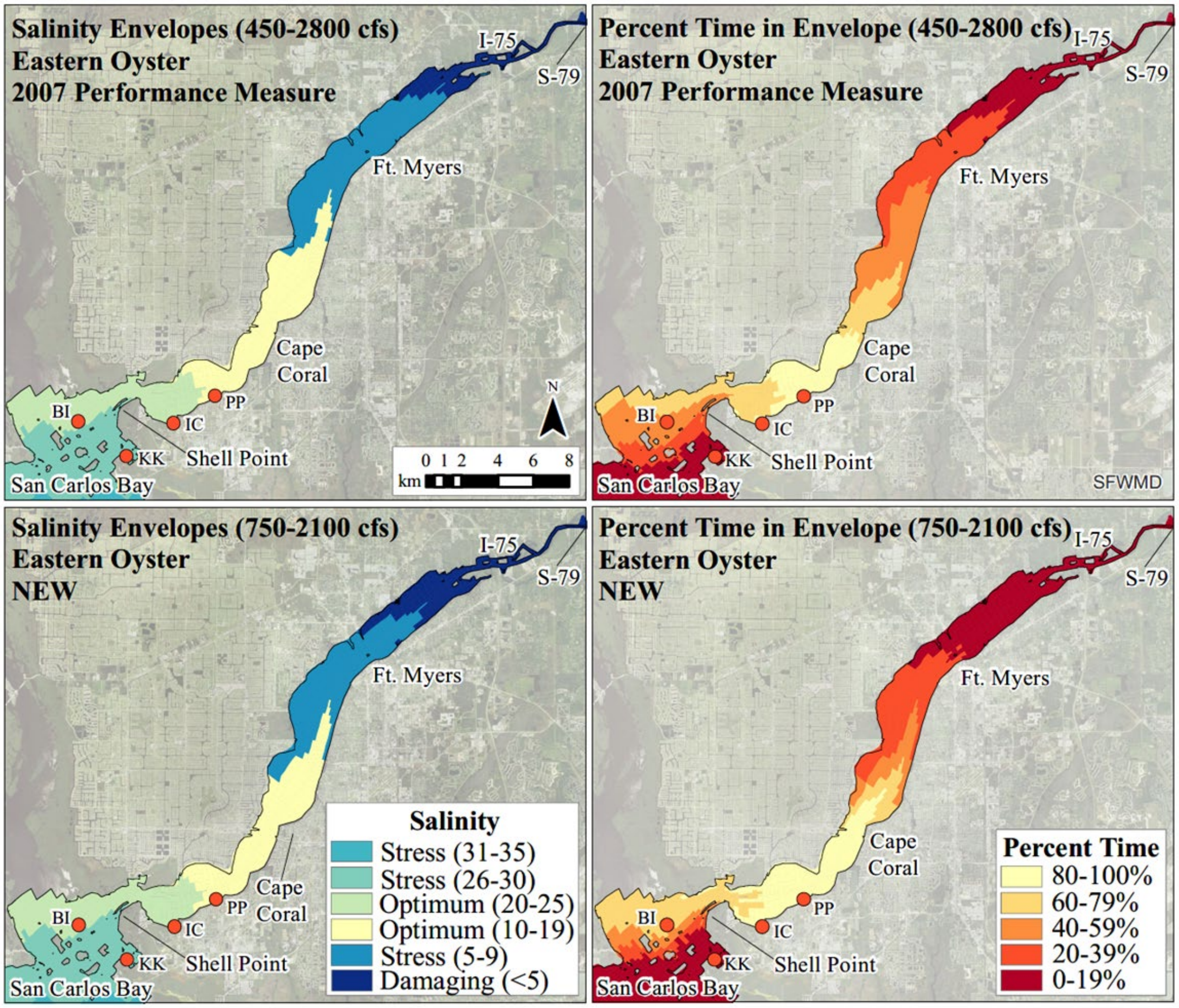

Figure 10. *Mean salinity and percent time within Optimum Salinity Envelope for Eastern oyster (salinities 10–25) in the Caloosahatchee River Estuary modeled on target flows from the 2007 PM (450–2800 cfs) and the new, revised PM (750–2100 cfs). Red circles indicate RECOVER oyster monitoring sites from 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.

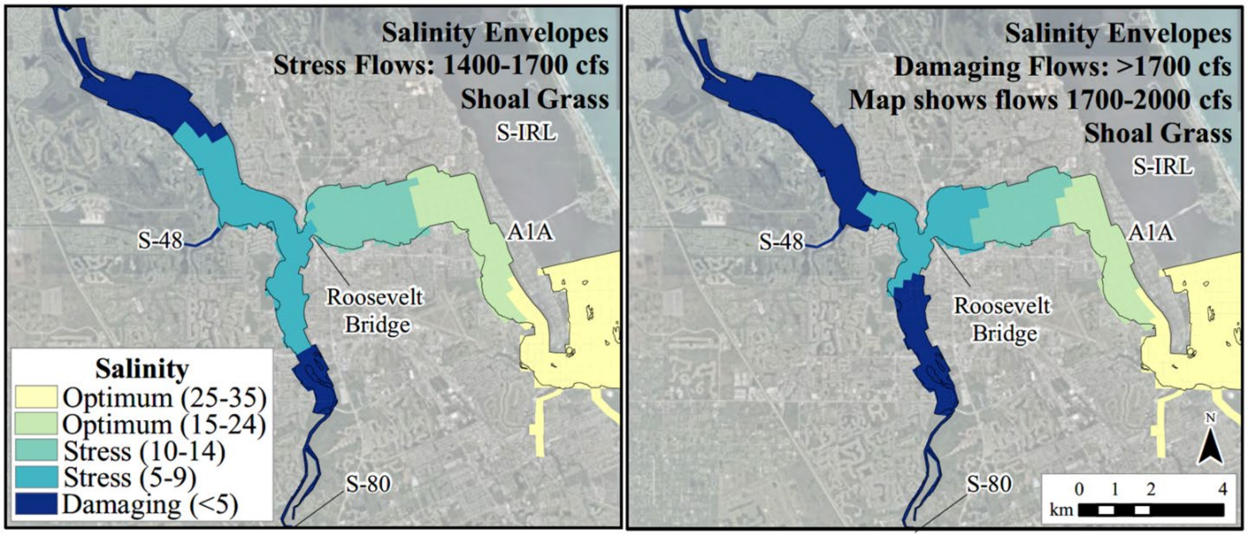

Figure 11. *Mean salinity ranges in the SLE for shoal grass (Optimum Salinity Envelope 15–45) resulting from Stress Flows 1400–1700 cfs (left) and Damaging Flows >1700 (right; depicts salinities resulting from flow 1700–2000 cfs). Salinities fall into the Stress Salinity Envelope for shoal grass (5–14)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

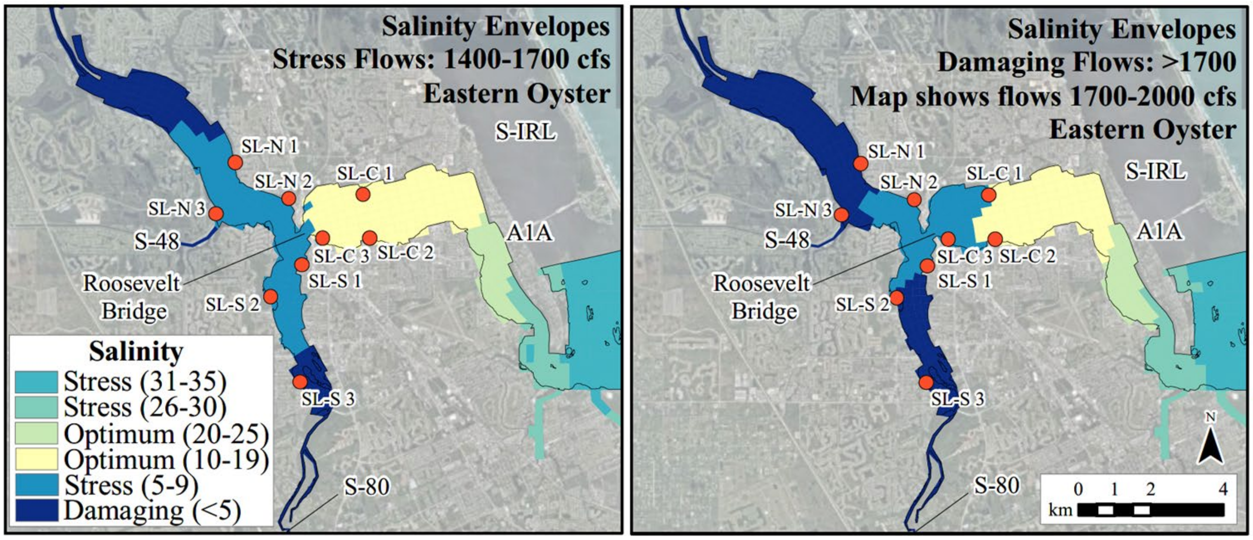

Figure 12. *Mean salinity ranges in the SLE for Eastern oyster (Optimum Salinity Envelope 10–25) resulting from Stress Flows 1400–1700 cfs (left) and Damaging Flows >1700 (right; depicts salinities resulting from flow 1700–2000 cfs). Red circles indicate RECOVER oyster monitoring sites: St. Lucie North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

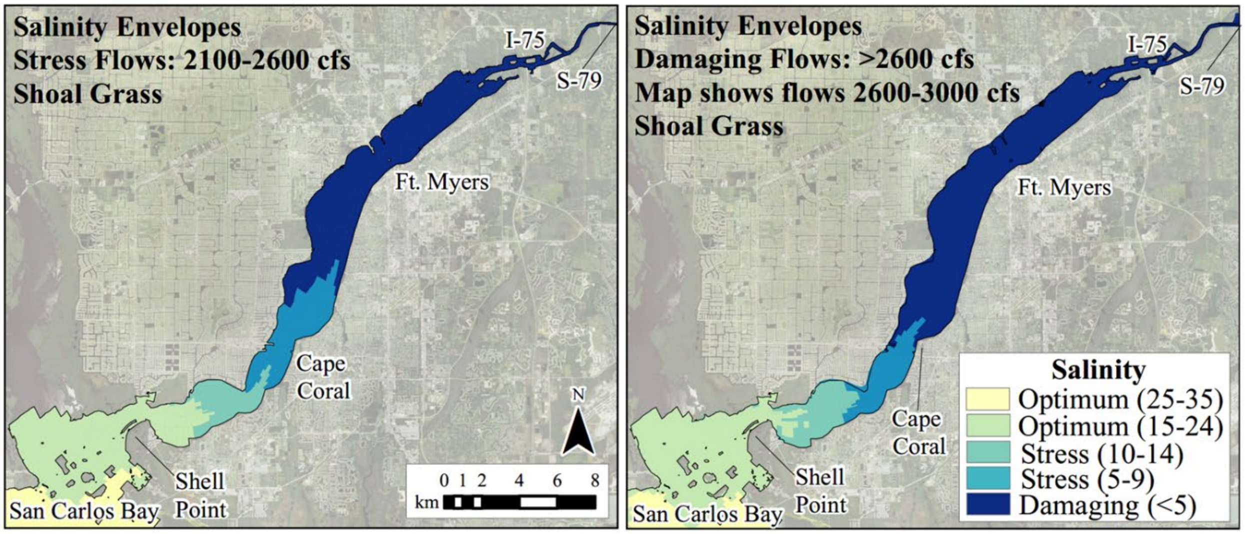

Figure 13. *Mean salinity ranges in the CRE for shoal grass (Optimum Salinity Envelope 15–45) resulting from Stress Flows 2100–2600 cfs (left) and Damaging Flows >2600 (right; depicts salinities resulting from flow 2600–3000 cfs). Salinities fall into the Stress Salinity Envelope for shoal grass (5–14) 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.*

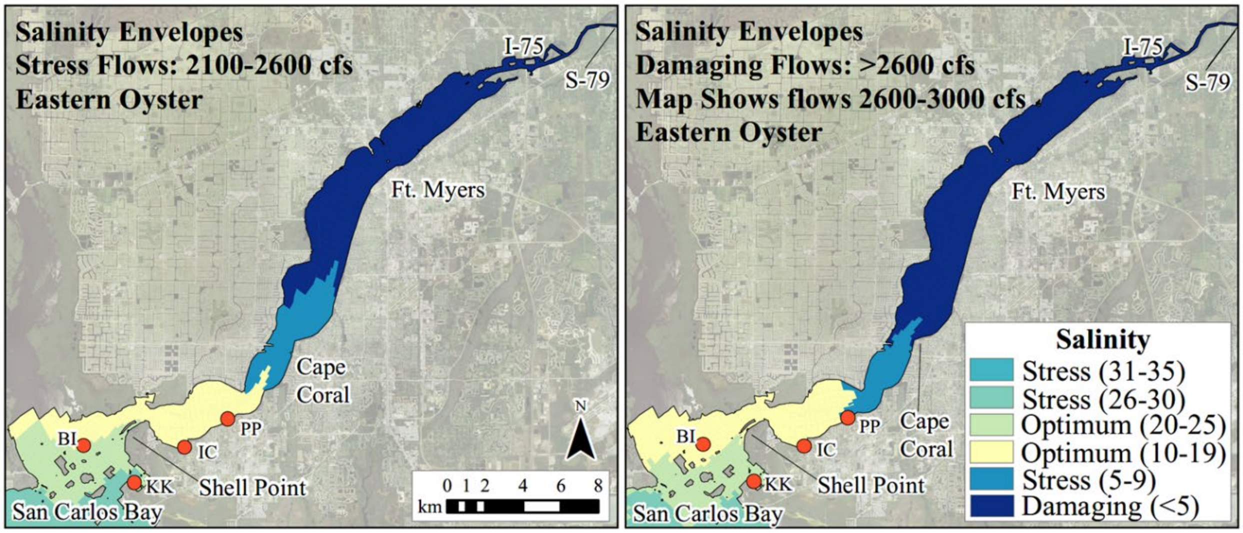

Figure 14*. Mean salinity ranges in the CRE for Eastern oyster (Optimum Salinity Envelope 10–25) resulting from Stress Flows 1400–1700 cfs (left) and Damaging Flows >1700 (right; depicts salinities resulting from flow 1700–2000 cfs). Red circles indicate RECOVER oyster monitoring sites from upstream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

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

Hypothesis Clusters (2009)
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

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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.

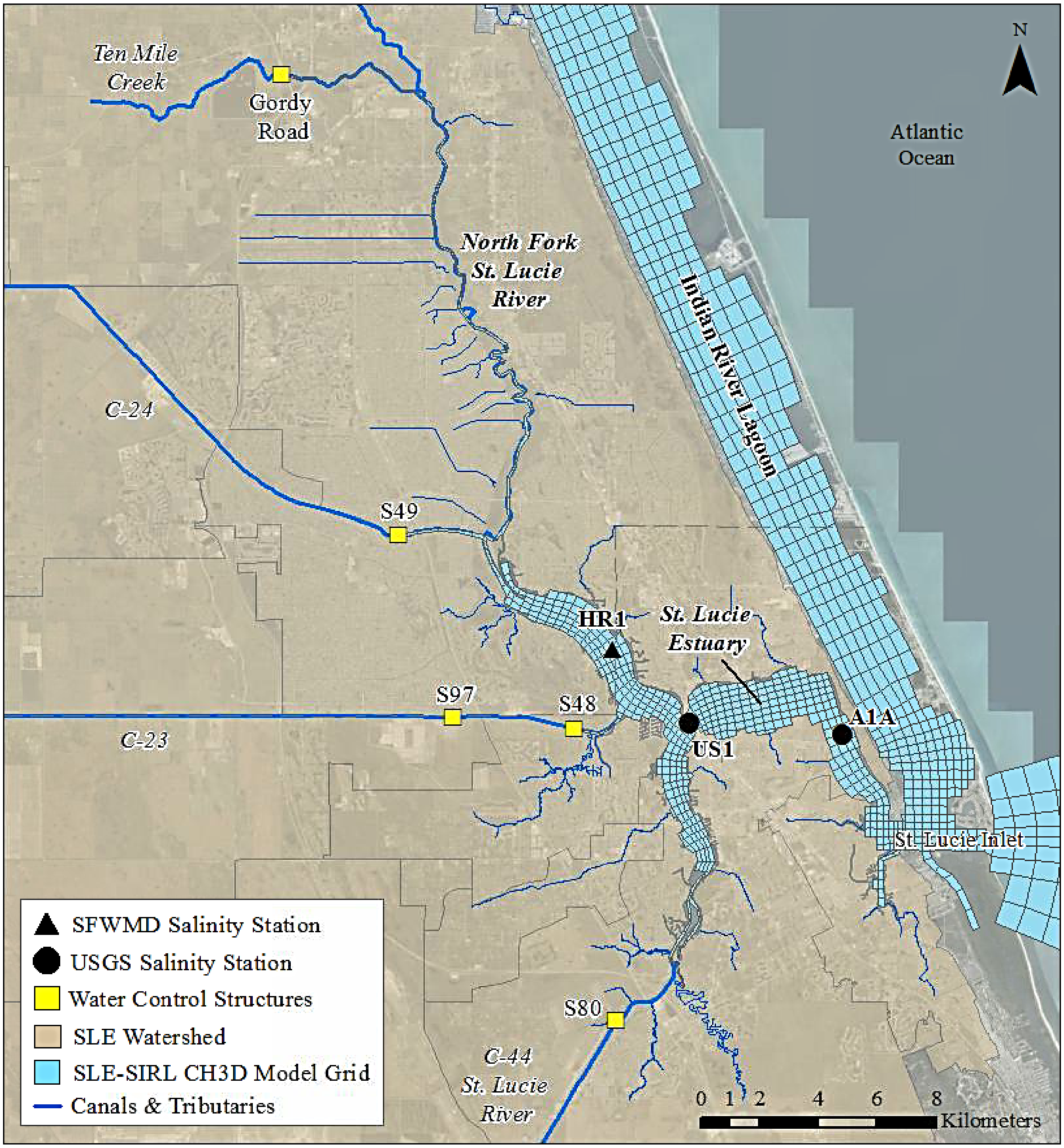

***Figure 1**. The CH3D model grid for the St. Lucie Estuary (SLE) and continuous data monitoring stations used for model calibration.*

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).

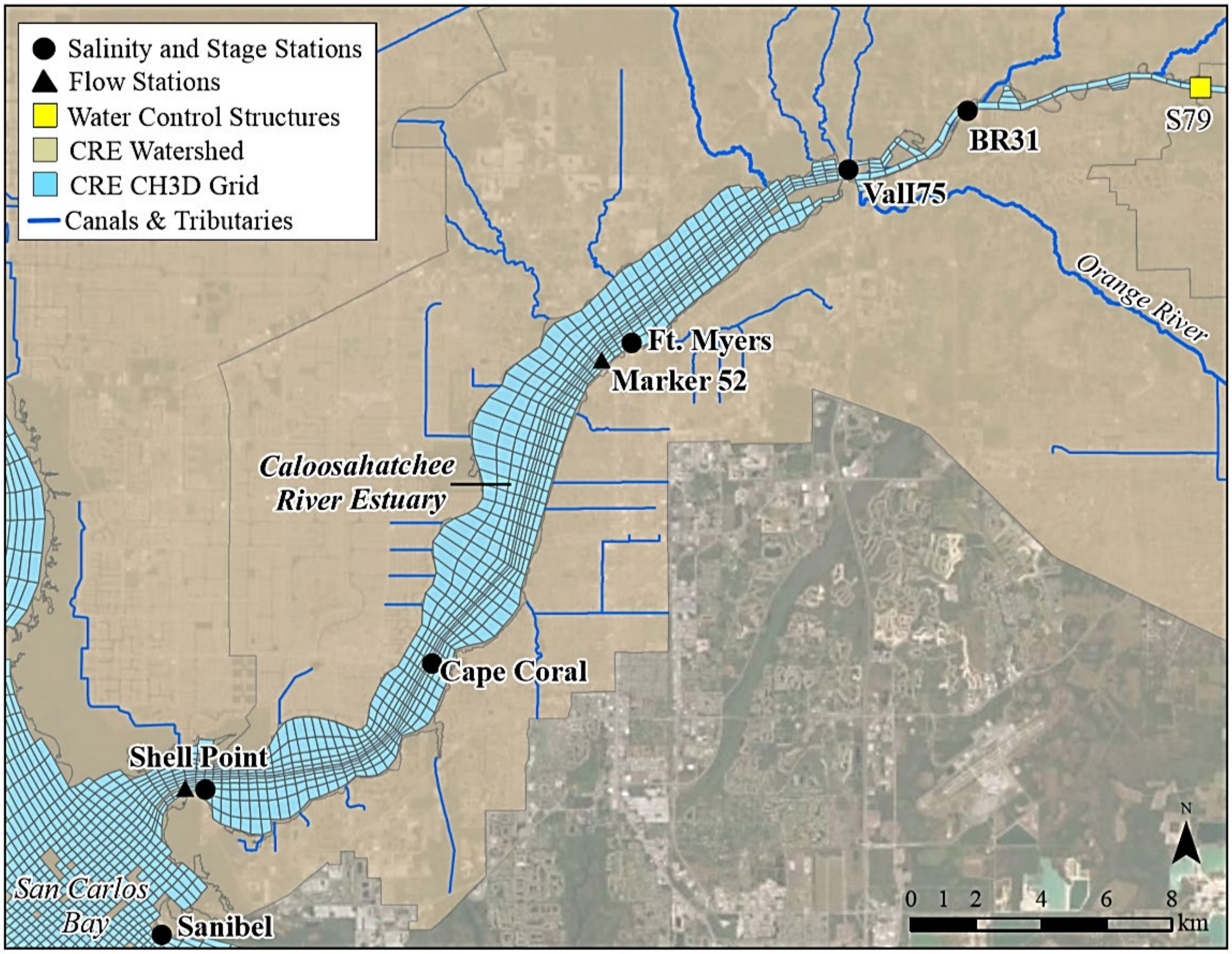

Figure 2. *The CH3D model grid for the Caloosahatchee River Estuary (CRE) and continuous data monitoring stations used for model calibration.*

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

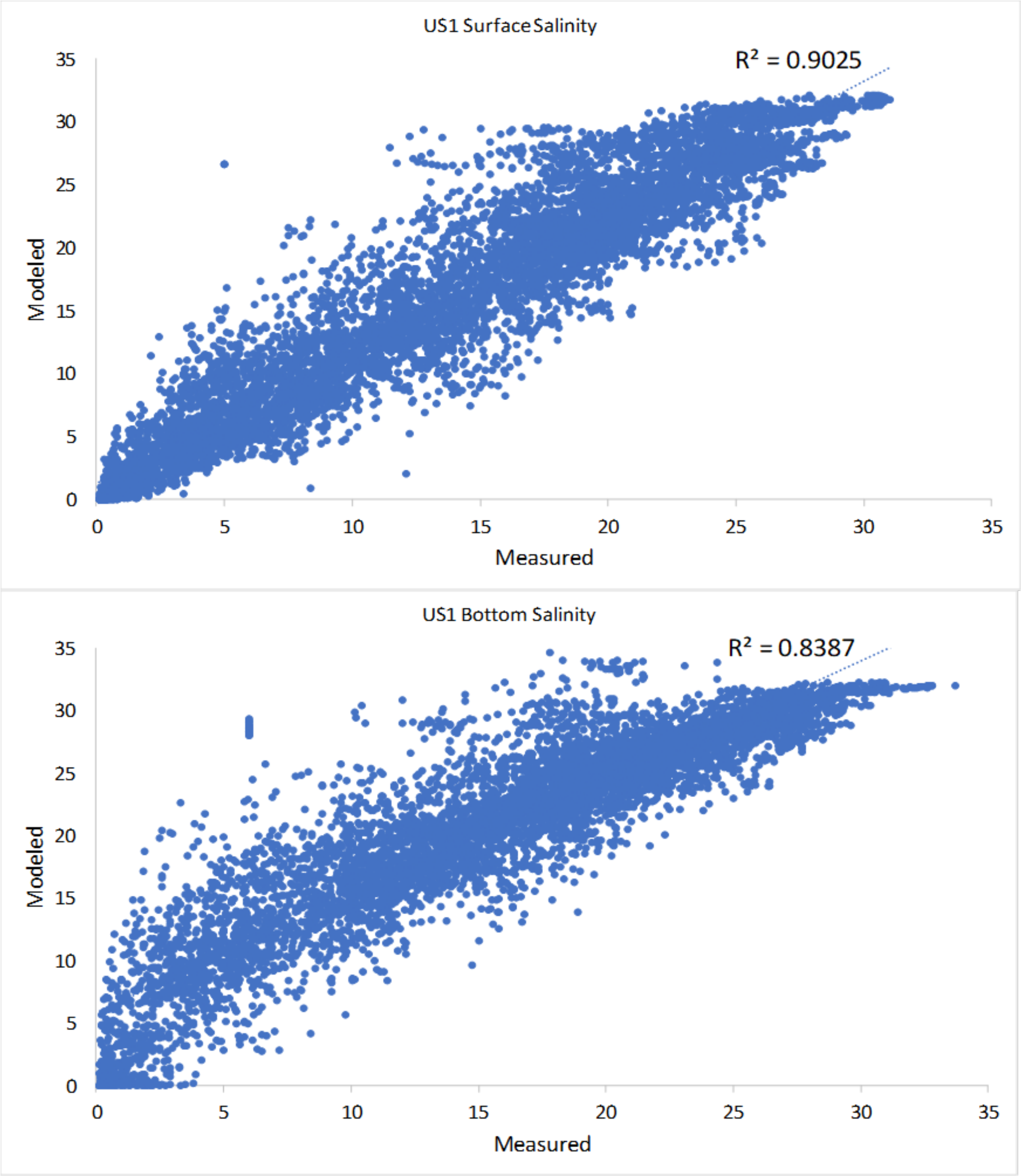

Figure 3. *Modeled daily surface (top) and bottom (bottom) water salinity vs. measured at US-1 Roosevelt Bridge in the SLE for the 15-year period from 2000 to 2015.*

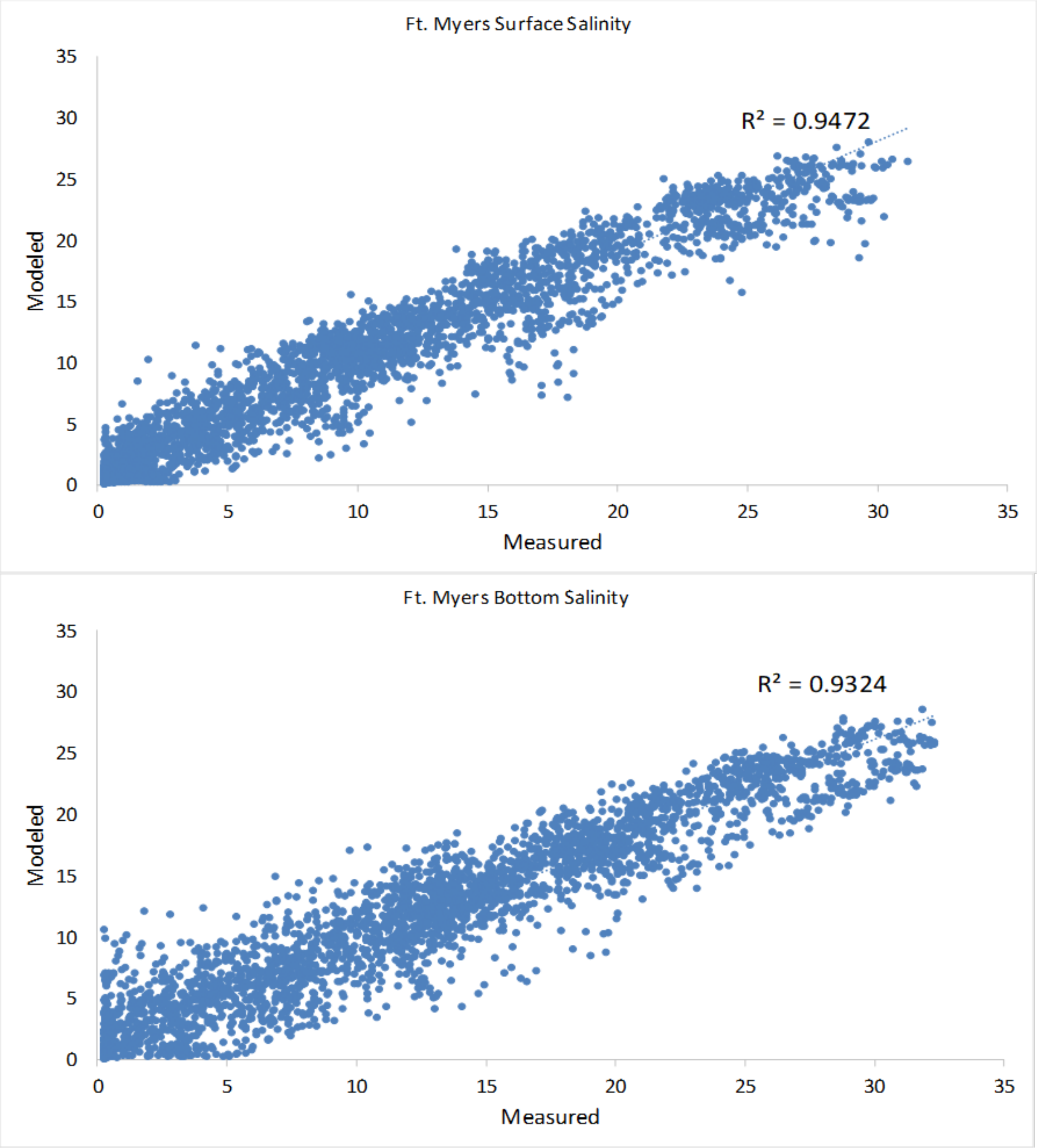

Figure 4. *Modeled daily surface (top) and bottom (bottom) water salinity vs. measured at Ft. Myers in the CRE for the 15-year period from 2000 to 2015.*

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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 i^{th} 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 i^{th} 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.

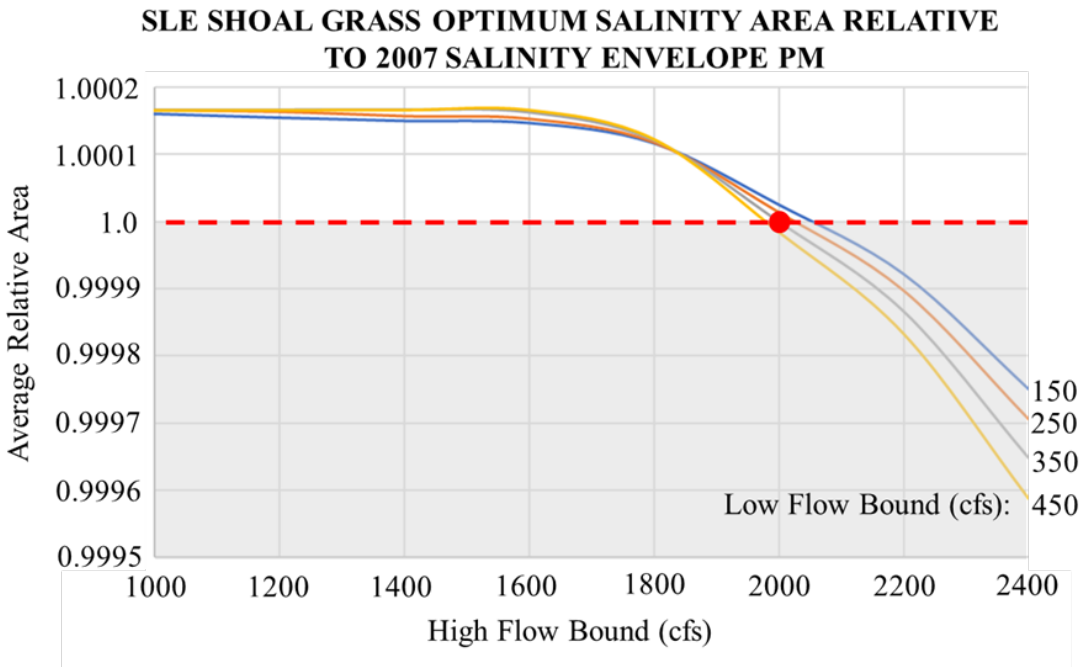

Figure 1. *St. Lucie Estuary (SLE) shoal grass Optimum Salinity (salinities 15–45) area, i.e., Potential Habitat Area (PHA) based on 14-day average salinity, relative to the SLE 2007 Salinity PM Flow Envelope (red dot: 350–2000 cfs, a score of 1.0 on the y-axis). High flow bounds on the x-axis, low flow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

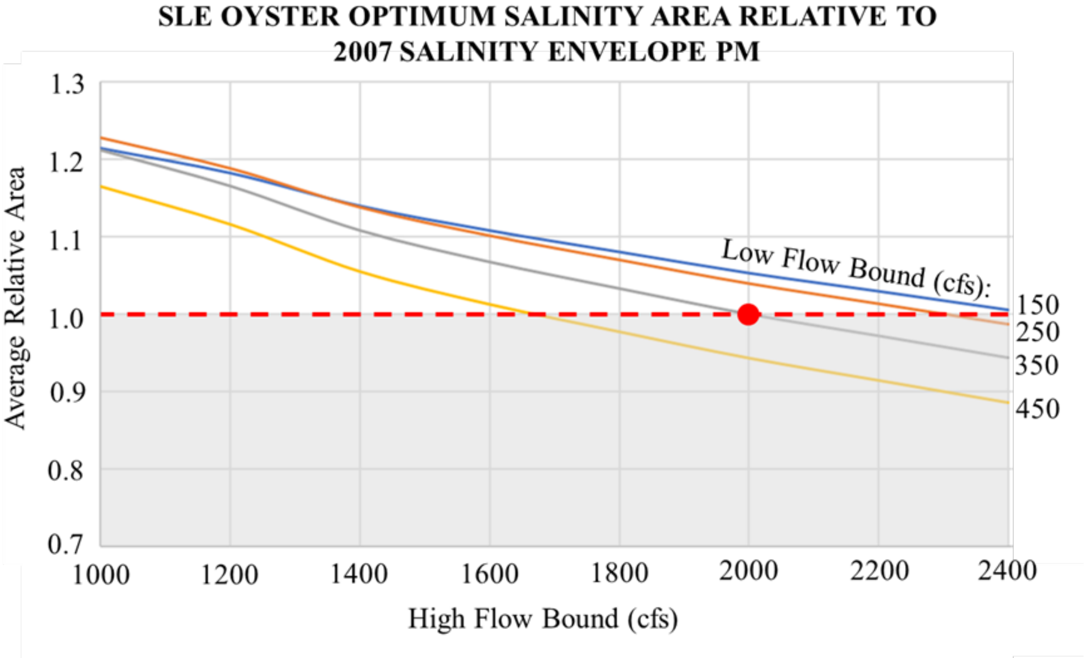

***Figure* 2**. *St. Lucie Estuary (SLE) Eastern oyster Optimum Salinity (salinities 10–25) area, i.e., Potential Habitat Area (PHA) based on 14-day average salinity, relative to the SLE 2007 Salinity Envelope PM flow envelope (red dot: 350–2000 cfs, a score of 1.0 on the y-axis). High flows are on the 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).

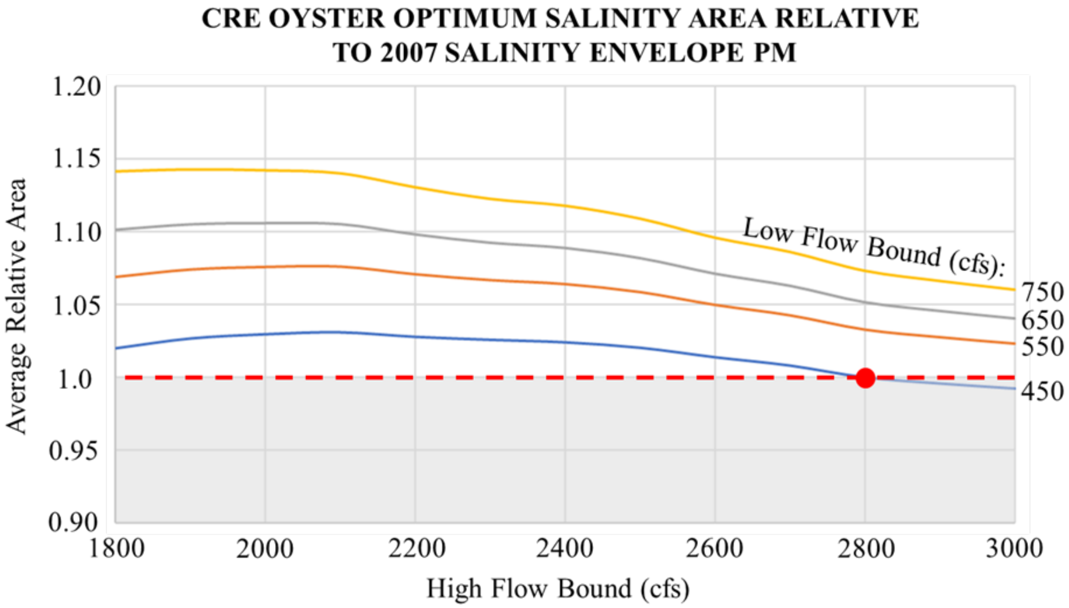

***Figure 3**. Caloosahatchee Estuary (CRE) Eastern oyster Optimum Salinity (salinities 10–25) area, i.e., Potential Habitat Area (PHA) based on 14-day average salinity, relative to the CRE 2007 Salinity PM flow envelope (red dot: 450–2800 cfs, a score of 1.0 on the y-axis). High flow bounds represented 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%.*

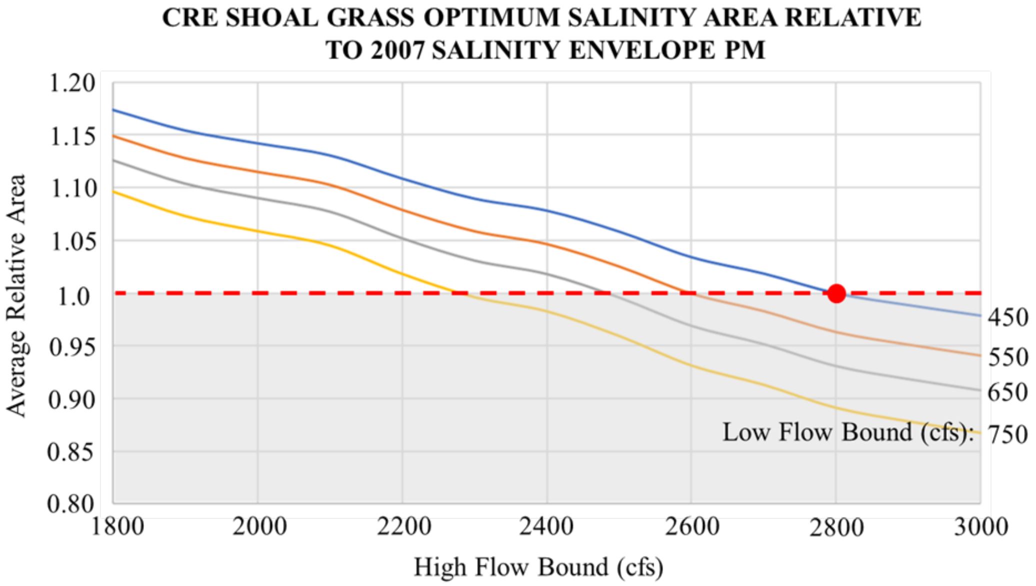

***Figure 4**. Caloosahatchee Estuary (CRE) shoal grass Optimum Salinity (salinities 15–45) area, i.e., Potential Habitat Area (PHA) based on 14-day average salinity, for the shoal grass, relative to the CRE 2007 Salinity PM flow envelope (red dot: 450–2800 cfs, a score of 1.0 on the y-axis). High flow 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%.*

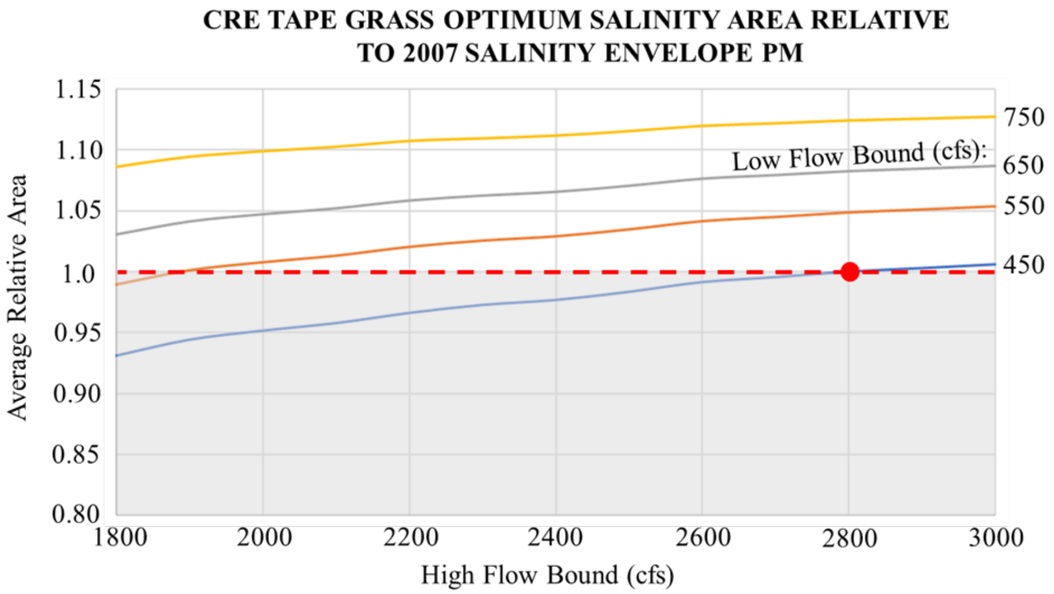

Figure 5*. Caloosahatchee Estuary (CRE) tape grass Optimum salinities (<10) area for the tape grass, i.e., Potential Habitat Area (PHA) based on 14-day average salinity, relative to the CRE 2007 Salinity PM flow envelope (red dot: 450–2800 cfs, a score of 1.0 on the y-axis). High flow bounds represented 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).

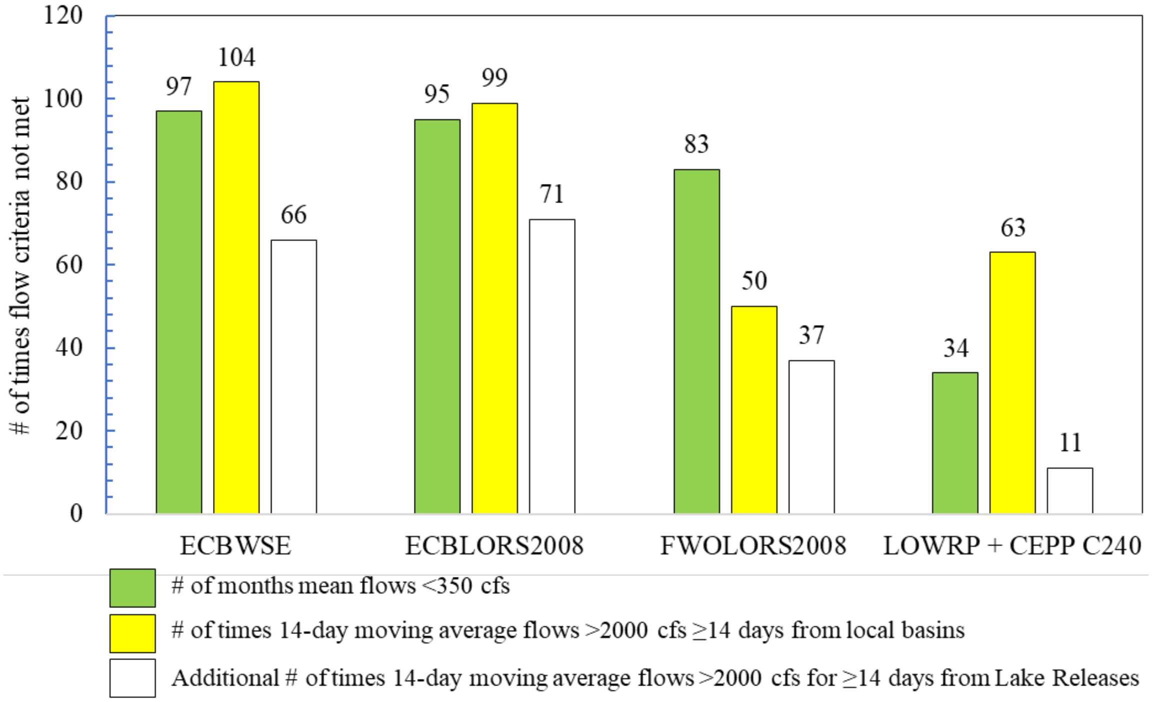

Figure 6*. Number of times the 14-day moving average or monthly flows to the SLE fell below and above the 2007 Salinity Envelope (RECOVER 2007) of 350–2000 cfs between the four condition simulations, over the period of record (1965–2005).*

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.

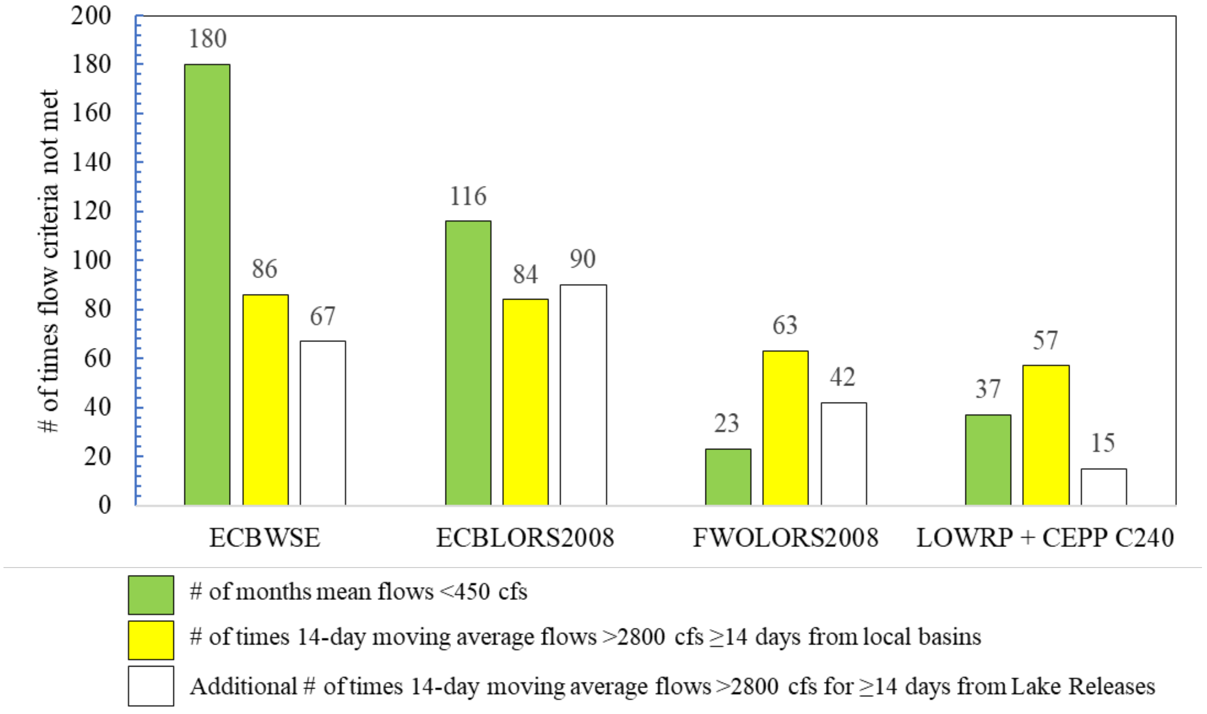

***Figure** 7. Number of times the 14-day moving average or monthly flows to the CRE fell below and above the 2007 Salinity Envelope (RECOVER 2007) of 450–2800 cfs between the four condition simulations, over the period of record (1965–2005).*

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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