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.

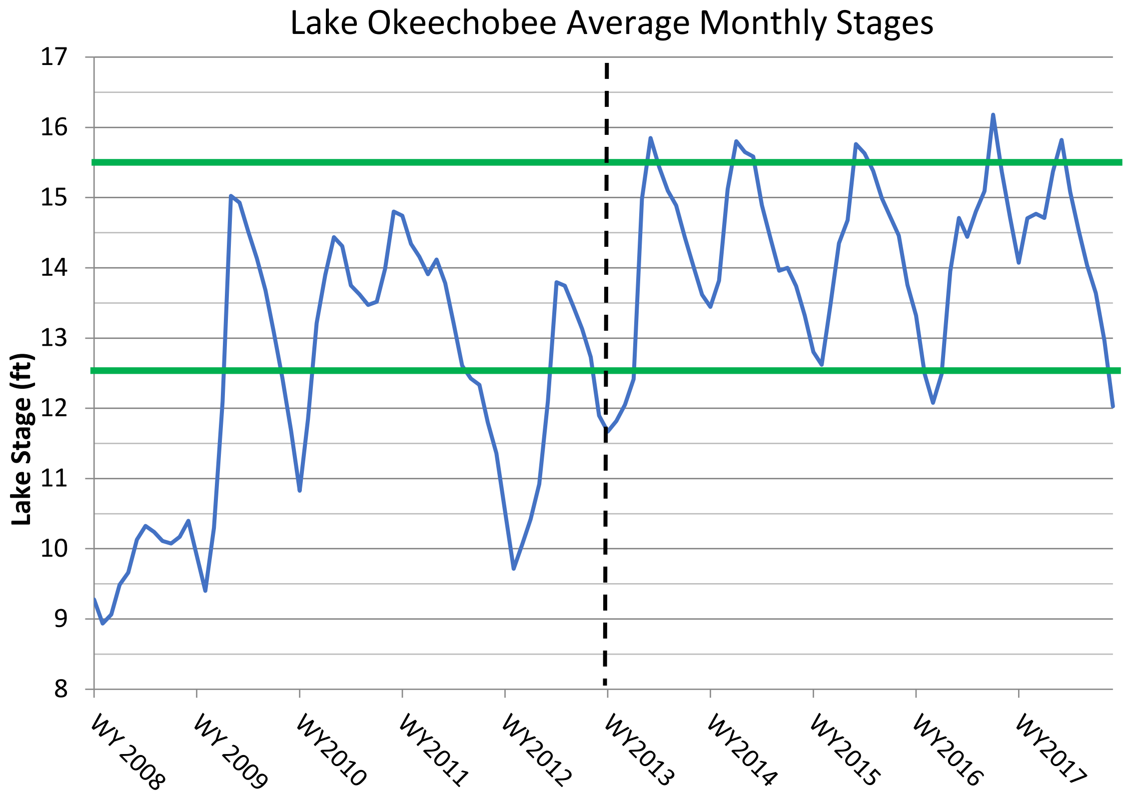

Figure 1. Lake Okeechobee average monthly stages from water year (WY) 2008 – 2017, or May 1, 2007 to April 30, 2017, using USACE average lake stage. Green horizontal lines indicate the top and bottom stages of the original ecological envelope and the vertical line is where WY2013-2017 period begins.

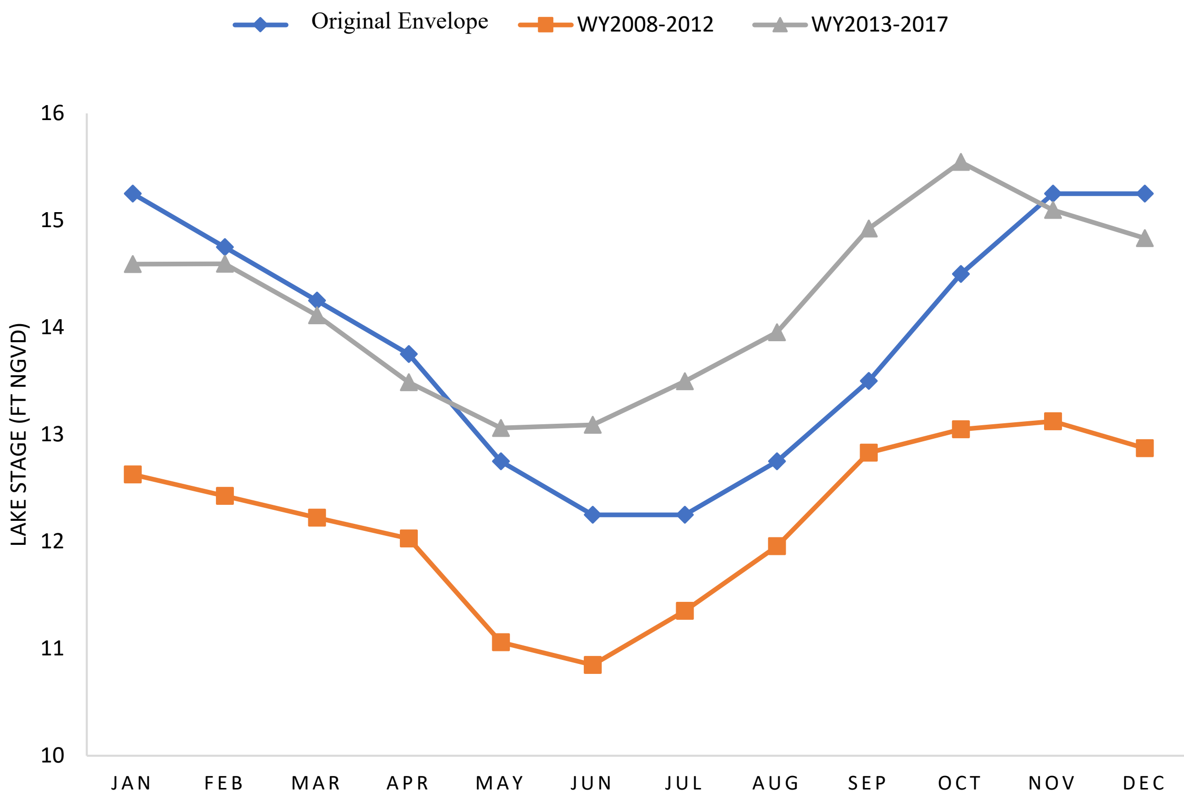

Figure 2. Average monthly lake stage for the original ecological envelope (blue), for WYs 2008-2012 (orange), and WYs 2013-2017 (gray), using the USACE average lake stage.

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.

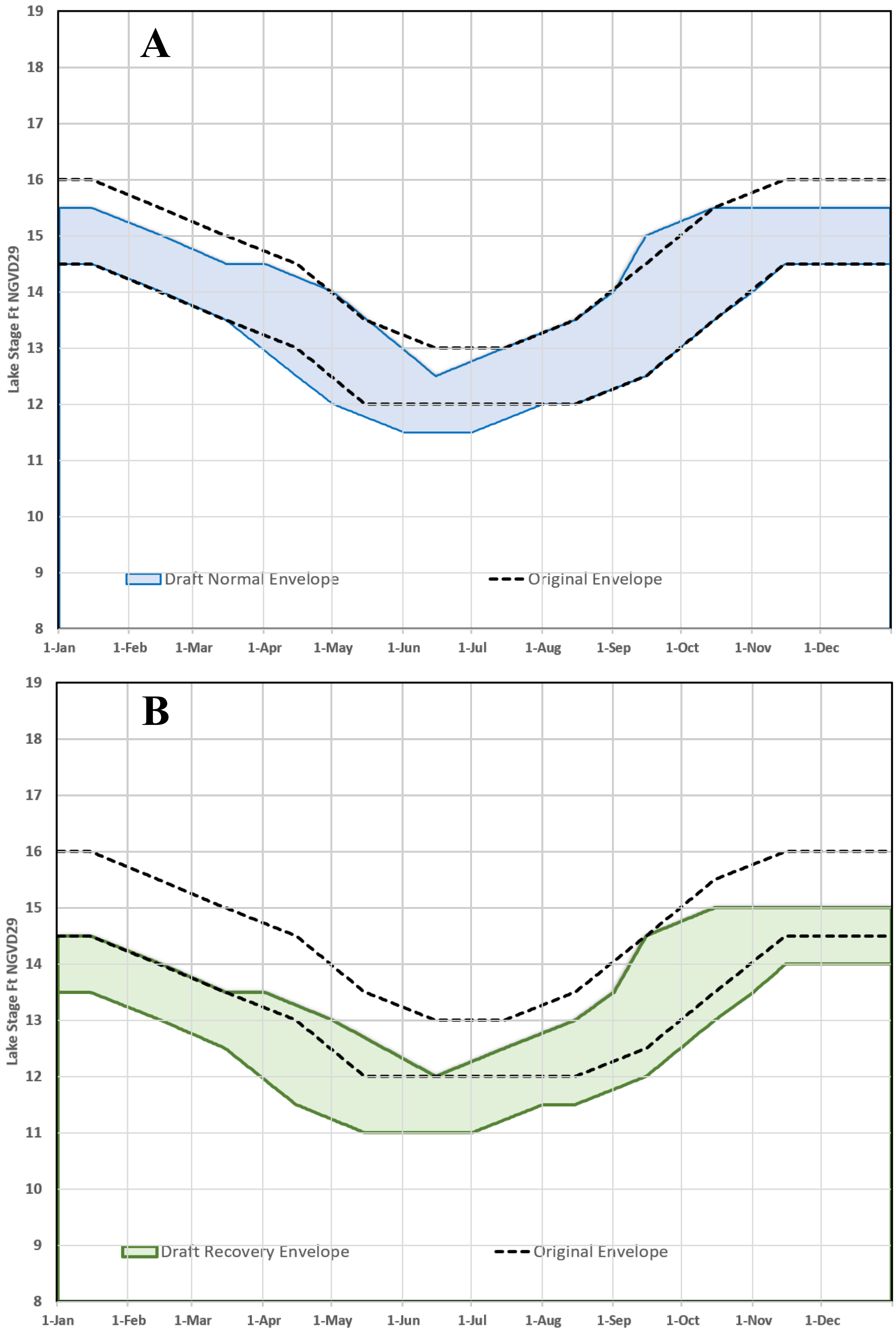

Figure 3. The original 2007 envelope (dashed) is shown relative to the **(A)** draft Normal envelope in blue and **(B)** the Recovery envelope in green.

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:

<u>Regional Models</u>
Lake Okeechobee

<u>Ecological Model for Hypothesis Clusters</u>

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.

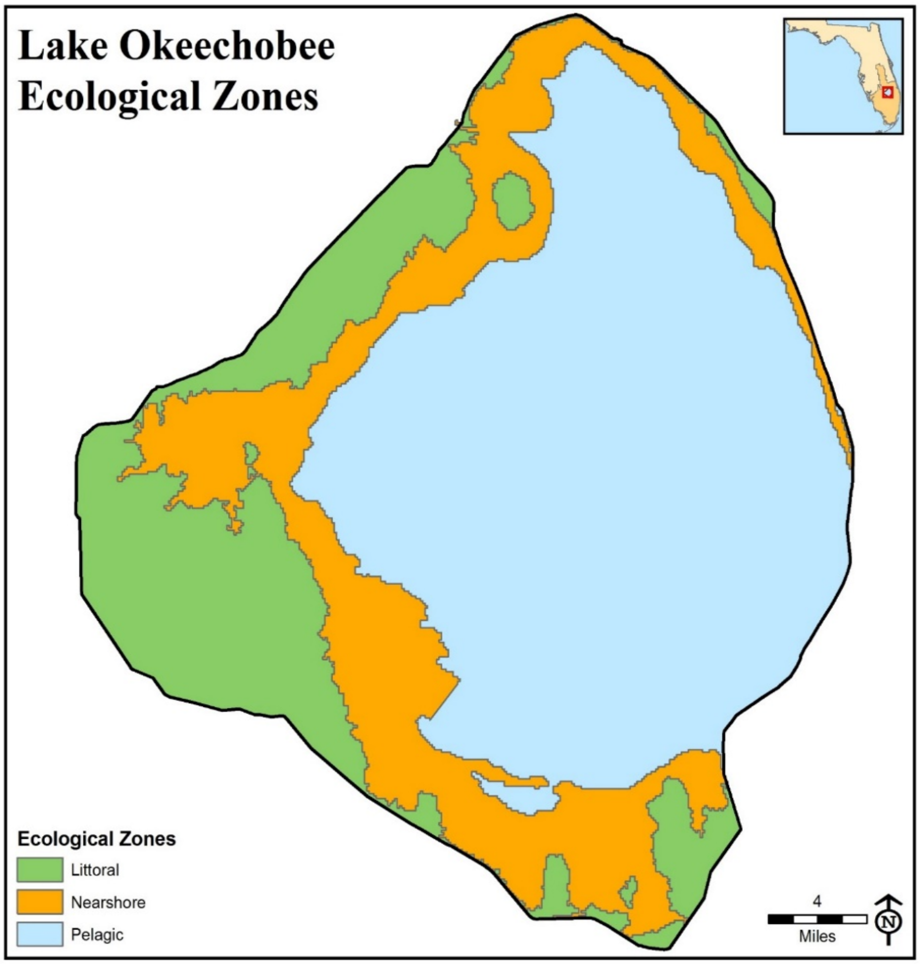

Figure 4. Lake Okeechobee ecological zones.

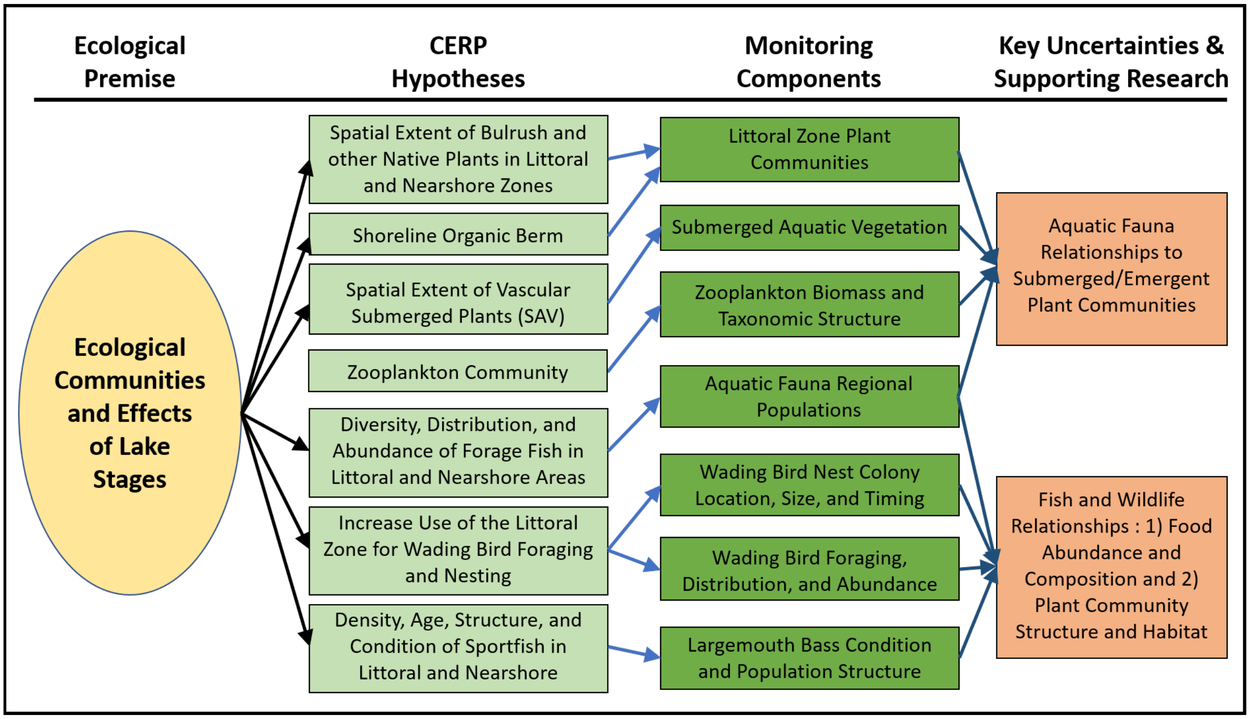

Figure 5. Conceptual framework showing relationships between ecological communities on the lake and water levels, or lake stage.

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.

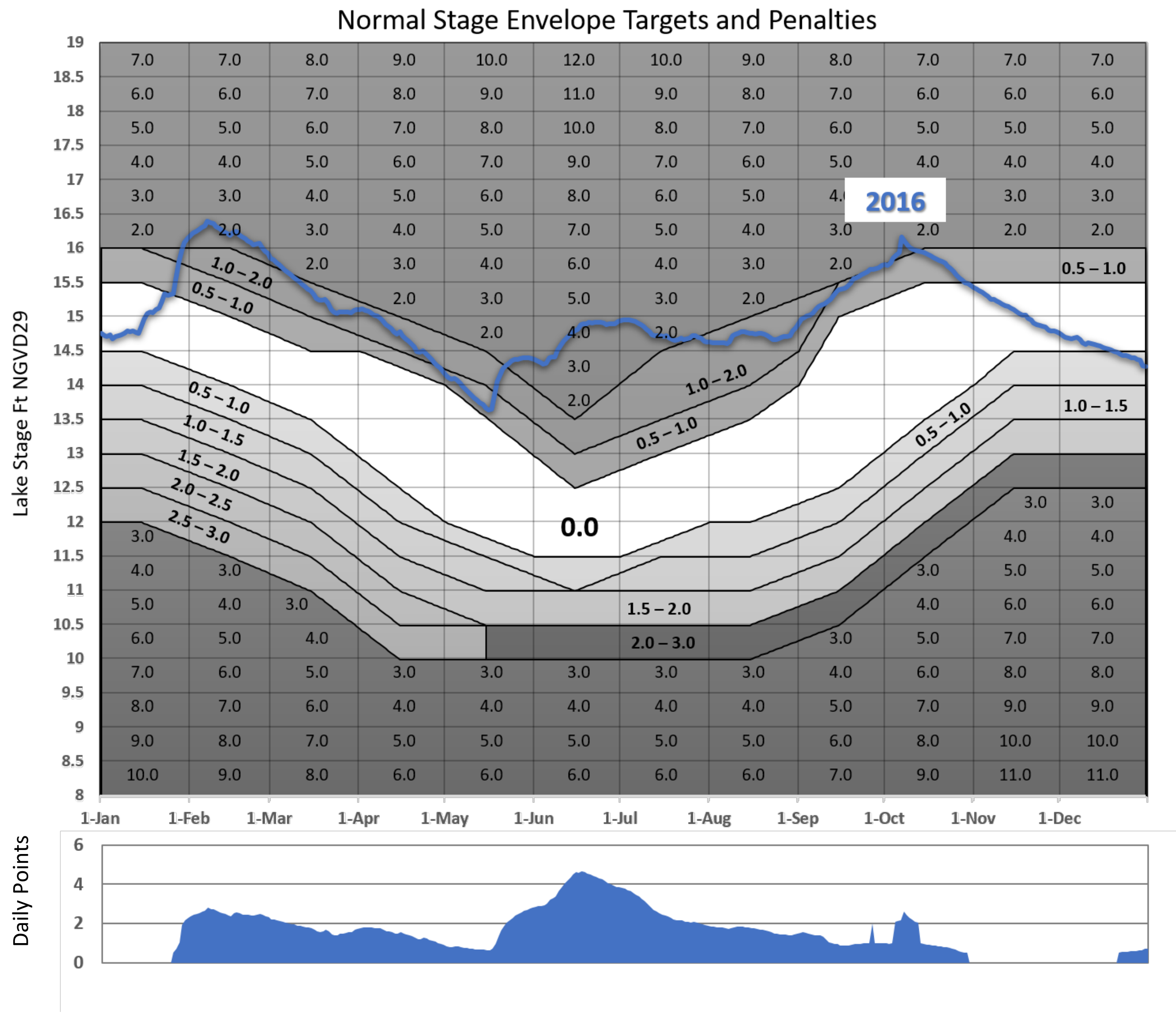

Figure 6. The Normal lake stage envelope and approximate corresponding scores that apply for lake stages outside the desired range. Scores are actually applied by the hundredths of a foot on a daily basis and may not correspond exactly to the boxes shown. For reference and as an example, 2016 stages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

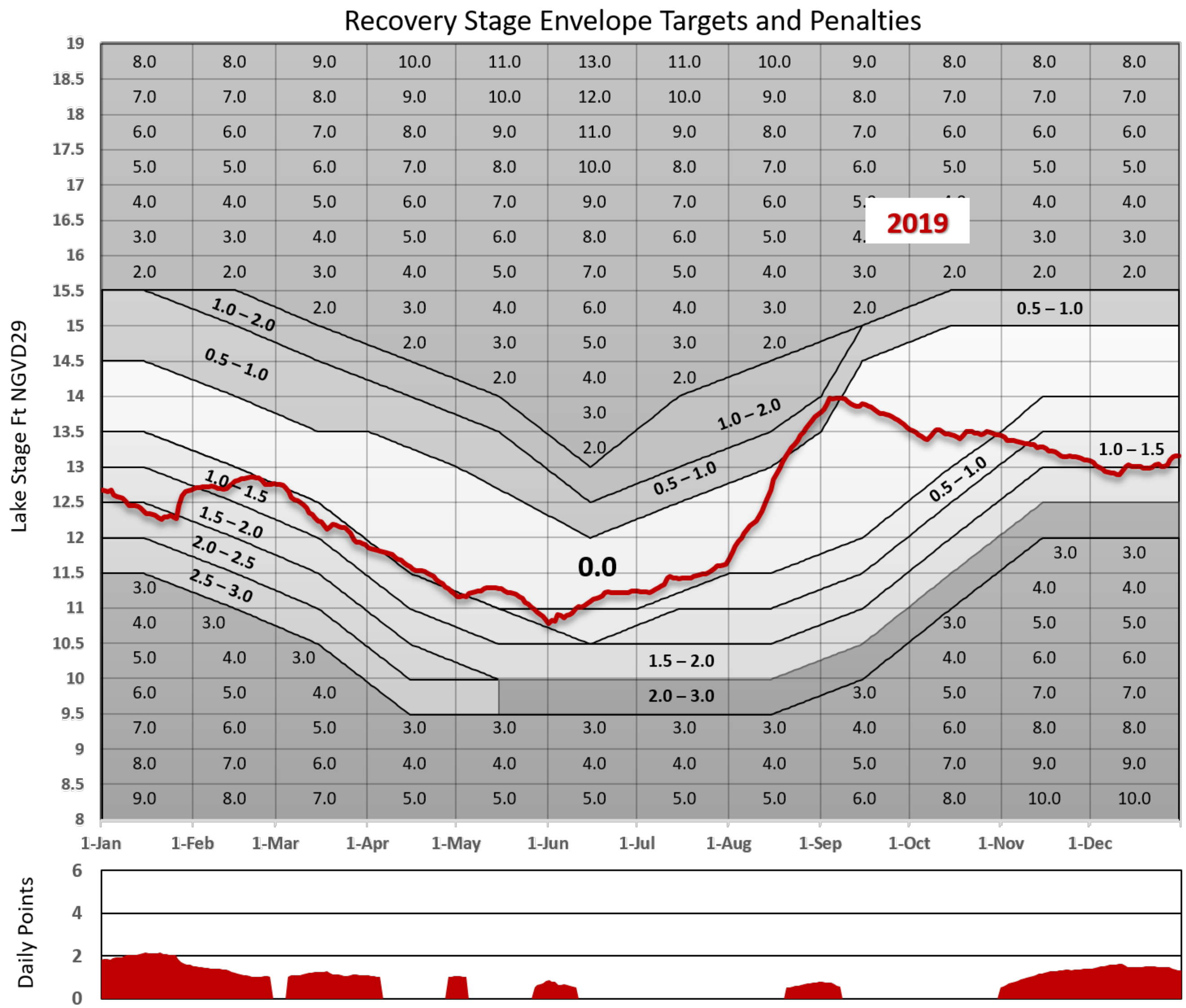

Figure 7. The Recovery lake stage envelope and approximate corresponding scores that apply for lake stages outside the desired range. Scores are actually applied by the hundredths of a foot on a daily basis and may not correspond exactly to the boxes shown. For reference and as an example, 2019 stages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

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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.

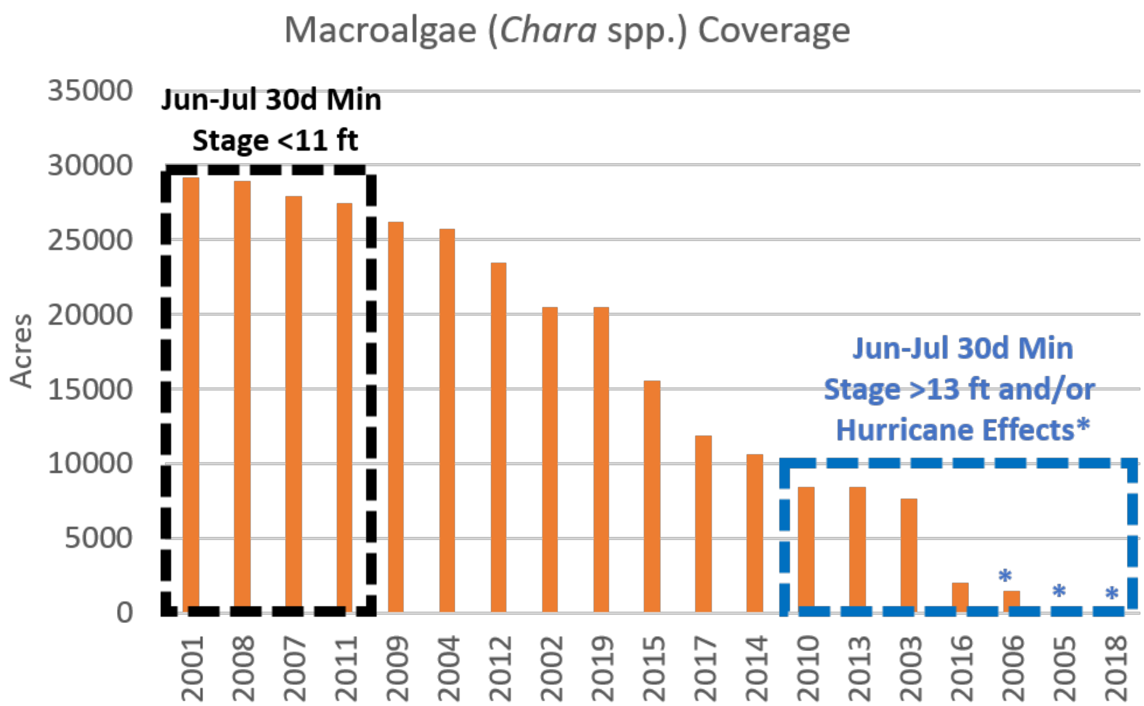

Figure A-1. Estimated maximum annual coverage (2001-2019) of *Chara* in descending order. Black dashed box represents low stage years in Figures A-2 and A-3 and blue dashed box represents high stage years in **Figures A-2** and **A-3**. Note that 2006 and 2018 did not have high summer stages but had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

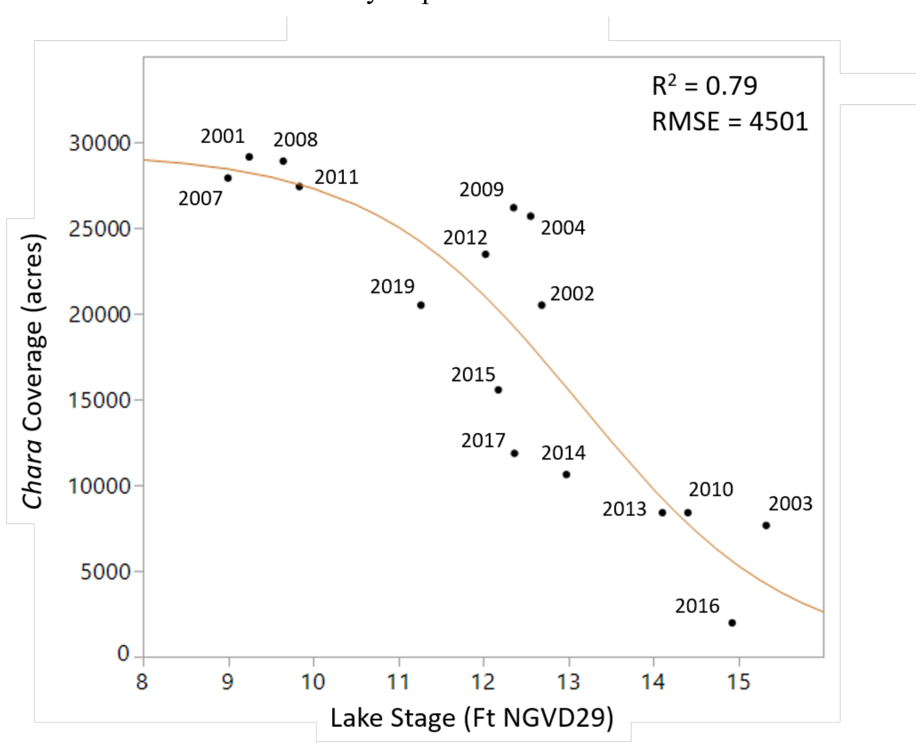

Figure A-2. A sigmoidal curve fit to estimated *Chara* coverage relative to the 30-day minimum stage from June through July. Years 2005, 2006 and 2018 were excluded due to hurricane effects on turbidity.

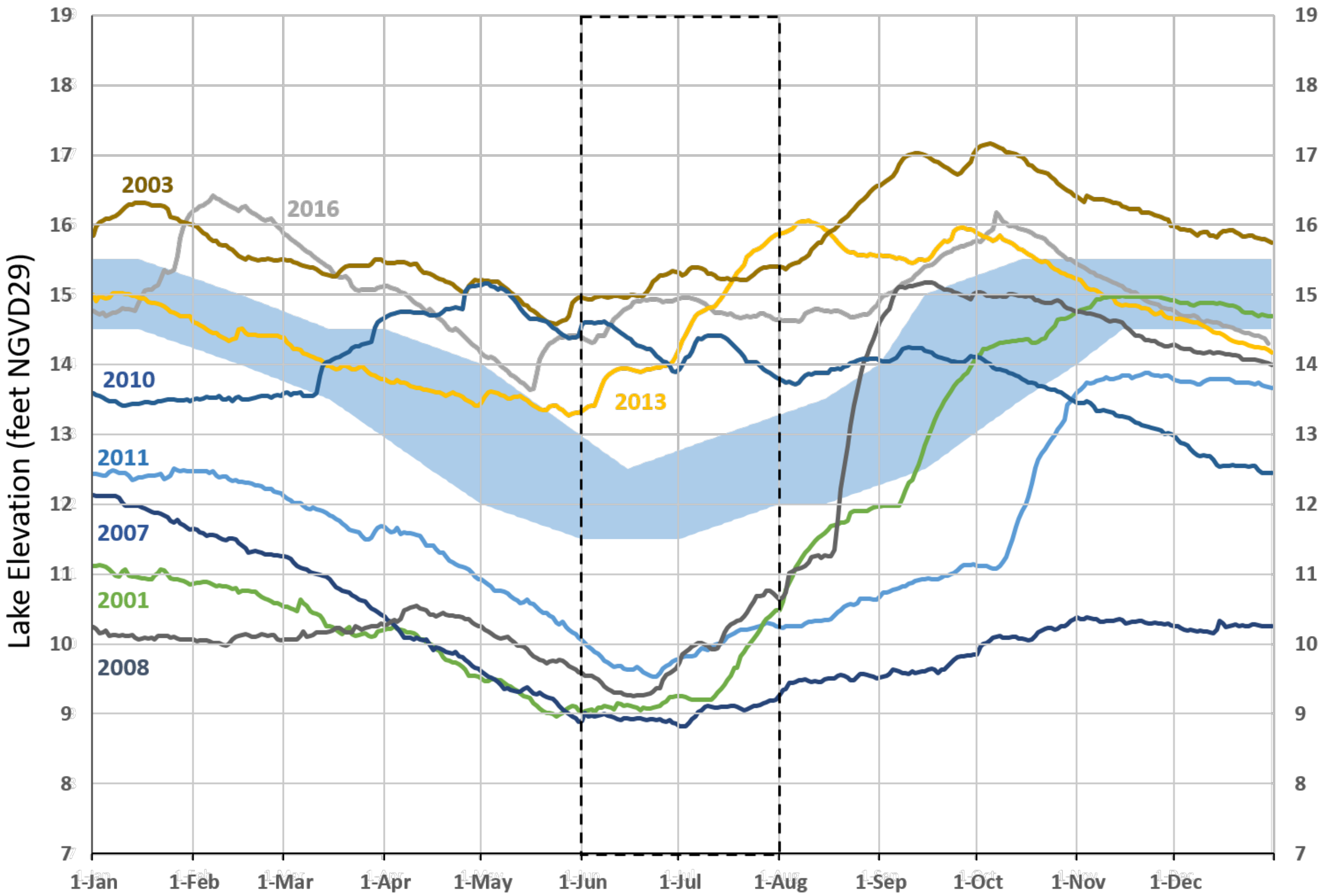

Figure A-3. Years with high and low lake stages in the summer that correspond to extremes in *Chara* coverage estimates in **Figure A-1**. The dashed box highlights the June-July period analyzed in Figure A-2 while the blue shaded area represents the proposed Ecological Envelope under normal conditions.

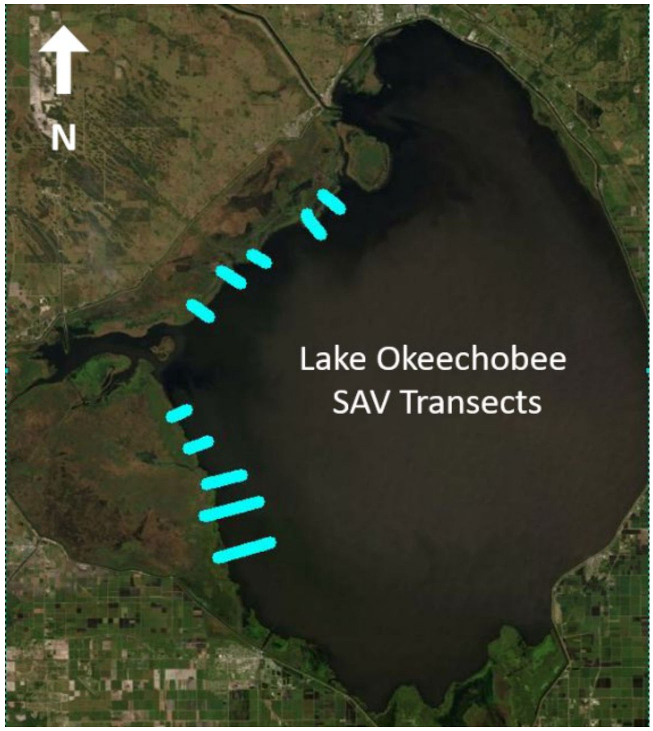

Figure A-4. Location of SAV monitoring transects established in 2018 that were used in **Figure A-5**.

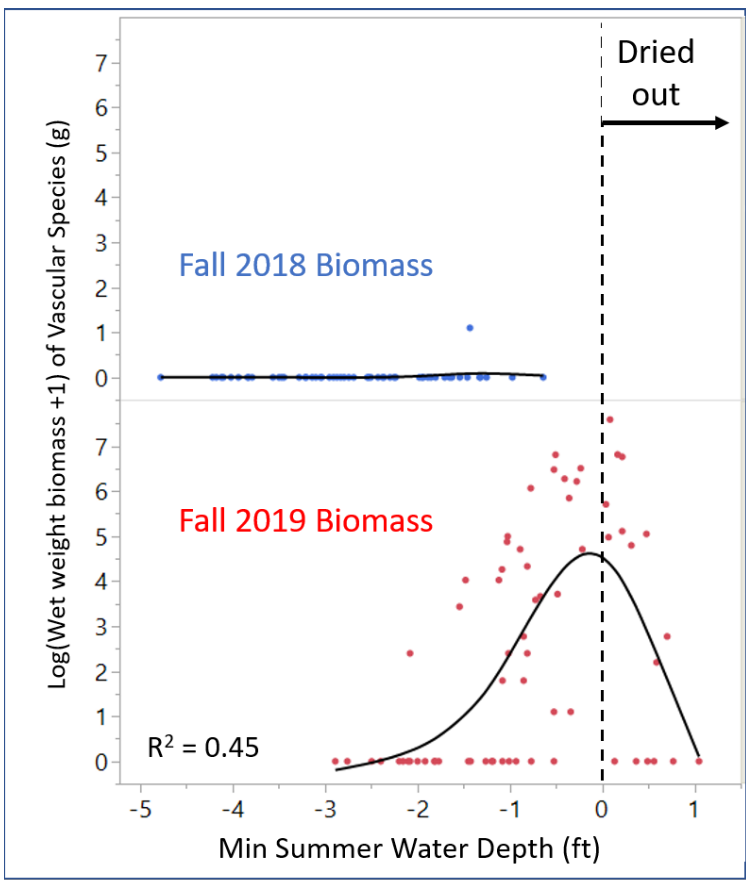

Figure A-5. Biomass of wet weight, vascular SAV (log[x +1]) in grams from SAV monitoring transects shown in **Figure A-4**. The dashed line represents the approximate elevation that was exposed at minimum summer lake stage. Smoothing spline (lambda 0.2) is fit to data for visual purposes.

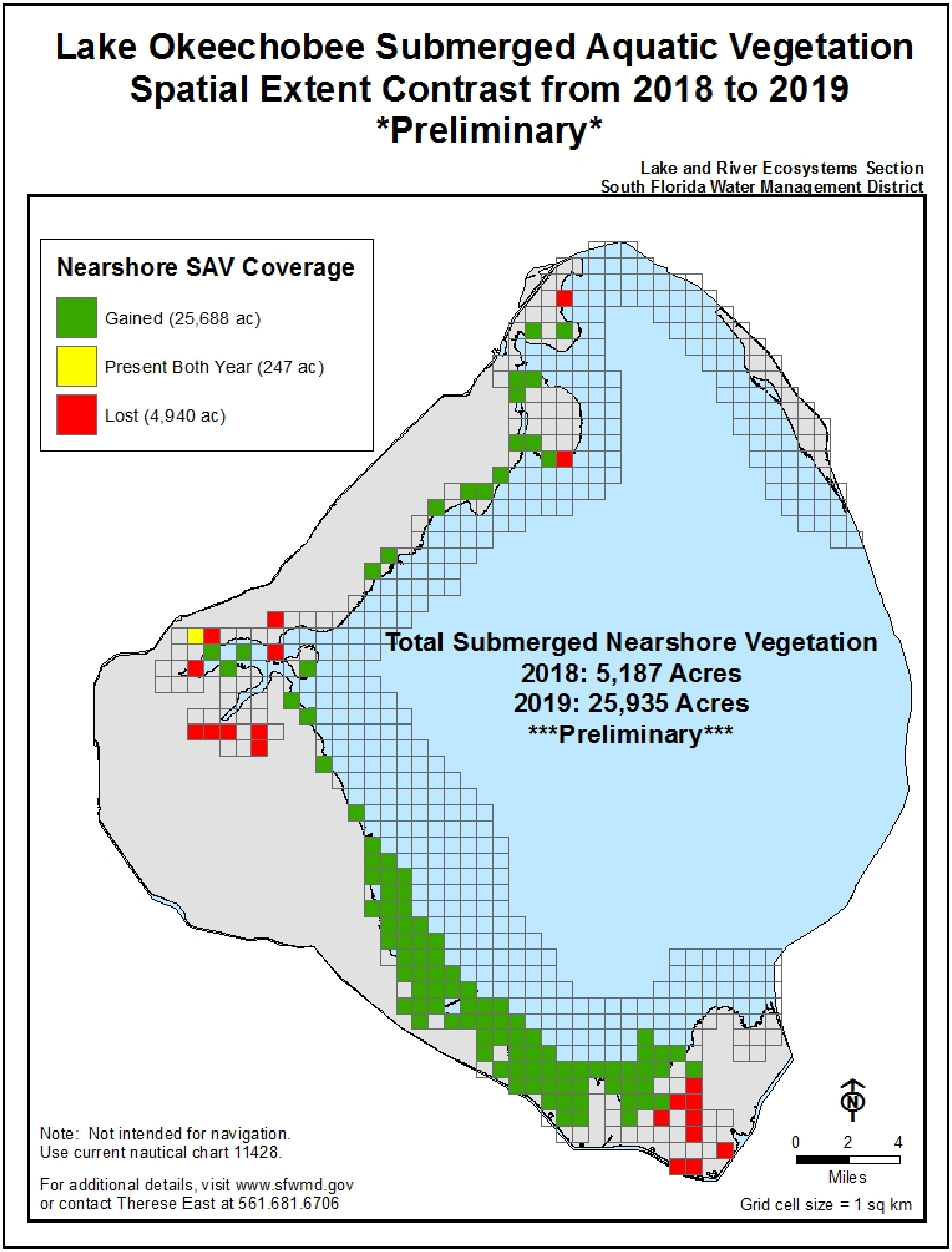

Figure A-6. Location of monitoring grids where SAV was gained (green), lost (red), or maintained (yellow) between August of 2018 – August 2019.