Scientific Synthesis to Inform Development of the New Lake Okeechobee System Operating Manual

An Independent Technical Review coordinated by the University of Florida Water Institute

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Findings and opinions expressed herein are the collective work of the author team and are based solely on analysis of pre-existing scientific literature and data.

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Executive Summary

Background and Technical Review Team Charge

The south Florida regional landscape was engineered by the Central and Southern Florida (C&SF) Project that was authorized by the Flood Control Act of 1948. The purposes of the C&SF are to: control floods; supply water to municipal, industrial, and agricultural users; prevent saltwater intrusion into wells; supply water for natural systems in the Everglades National Park (ENP); and supply water that preserves and protects fish and wildlife resources. The C&SF Project functions well in meeting its intended purposes of water supply and flood control. However, the regional project falls short in protecting natural environments. In fact, the regional project has caused considerable adverse impacts to the natural ecosystems of south Florida, including the St. Lucie Estuary, Caloosahatchee Estuary, Lake Okeechobee, the Florida Everglades, and Florida Bay. Such impacts stem from large deviations in the quantity, quality, timing and distribution of freshwater delivered to these systems relative to pre-engineered conditions.

The C&SF Project was designed with Lake Okeechobee serving as the central water storage area. Unlike most flood-control reservoirs, Lake Okeechobee currently lacks a natural outflow that would enable rapid discharge of water when lake stage is high enough to potentially compromise the structural integrity of the surrounding levee. With the current infrastructure, hydrologic inputs to Lake Okeechobee may exceed outputs by a factor of 4-6 depending on rainfall, antecedent conditions in the drainage basin to the north, and water level in the lake. If substantial rain falls north of the lake, large inflows to the water body can quickly raise the lake level by several feet, thereby putting the levee at risk. Under such high-stage scenarios, water is released from the lake to avoid potential catastrophic flooding (USACE 2008). However, such water releases are highly constrained by many factors, including a lack of infrastructure that can move large volumes of water southward, the inability of the Water Conservation Areas south of the lake to receive substantial inflows without negative ecosystem impacts or flooding risks, and Federal regulations that restrict the amount of phosphorus-rich water that can be delivered to the Everglades. Consequently, canals east and west of the lake, which lead to the St. Lucie and Caloosahatchee Estuaries, respectively, are the main conduits for rapid removal of water from Lake Okeechobee when stage is deemed to be too high.

Water in Lake Okeechobee has become highly polluted with Phosphorus (P) and Nitrogen (N), primarily from agricultural sources north of the lake. Despite implementation of Best Management Practices (BMPs) in the Lake Okeechobee watershed, high nutrient loads to the lake continue, in part from legacy phosphorus and nitrogen that has accumulated in the system. As a result, when excessive rainfall in the northern basin leads to rapidly rising water levels in the lake, large discharges of nutrient-laden water are released to the northern estuaries. Furthermore, the St. Lucie and Caloosahatchee Watersheds are both expanded by canals and heavily developed for agricultural and urban uses, so they provide additional inputs of freshwater and nutrients after heavy rains. Large, nutrient-enriched freshwater discharges to the estuaries can have profound physical, chemical, and biological effects on the receiving water bodies, and sometimes lead to harmful algae blooms and negative impacts to valued biological components of the ecosystem, such as submerged aquatic vegetation (SAV) and oyster beds. These ecological and environmental impacts, in turn, influence the socio-economic landscape in south Florida, with far-reaching and potentially long-lasting, negative consequences.

In 2008, concern about the safety of the Herbert Hoover Dike (HHD) that surrounds Lake Okeechobee led to the implementation of a new Lake Okeechobee Regulation Schedule (LORS2008). LORS2008 was designed to hold the lake at lower levels until a rigorous evaluation of the risk of dike failure and modifications to the dike to reduce risk to an acceptable level were completed. The HHD Rehabilitation is scheduled for completion in 2022. Planning for the next phase of the Lake Okeechobee System Operating Manual (LOSOM) began in January 2019 and is expected to be complete by December 2022. New infrastructure that will soon be operational and will be incorporated into the next LOSOM includes the Kissimmee River Restoration Project (scheduled for completion in 2020), the Indian River Lagoon South C-44 Reservoir and Stormwater Treatment Area (scheduled for completion in 2022), and the C-43 Western Basin Storage Reservoir (scheduled for completion in 2024). The Central Everglades Planning Project (CEPP), including the associated Everglades Agricultural Area (EAA) reservoir, is not scheduled for completion until 2028 or beyond, and thus will not be included in the next LOSOM.

Given the complexity of the issues related to developing the next LOSOM, and the large number of potentially affected stakeholders, the South Florida Water Management District (SFWMD) contracted with the University of Florida (UF) Water Institute to coordinate an independent effort to acquire and synthesize available technical literature and data to inform future LOSOM development.

Challenges to Reducing High-Volume Freshwater Flows to the Estuaries

There are a number of fundamental challenges to reducing the frequency and duration of freshwater discharges, with associated nutrients and algae, to the St. Lucie and Caloosahatchee Estuaries. These challenges include: the complex and inter-connected nature of the Greater Everglades system, with its flat topography, porous geology and highly variable climate; the footprint of the Everglades system having been reduced to approximately half its original size; the much larger capacity of canals and structures that deliver inflow to Lake

Okeechobee relative to those that carry outflow; the much smaller capacity of outflow canals and structures that can carry water south of Lake Okeechobee versus those that deliver water east and west; flooding risks in agricultural and urban areas immediately surrounding and farther southeast of Lake Okeechobee; impacts on the Lake Okeechobee ecosystem associated with periods of extreme high and low lake levels; legal limits for phosphorus loading to the Everglades Protection Area (EPA) and Everglades National Park (ENP); regulation schedules for the Water Conservation Areas (WCAs) in the EPA, intended to protect ridge, slough and tree island habitats and associated wildlife; constraints imposed by the existing and sometimes conflicting rights of legal water users; and the need to comply with existing laws and court orders. The UF Water Institute Report to the Florida Senate (Graham et al. 2015) provides more complete information on each of these constraints.

Repeated planning exercises have shown that large volumes of inter-annual storage and associated water treatment are required north, south, east and west of Lake Okeechobee to manage Lake Okeechobee levels within a desirable range, reduce damage from high and low flows to the St. Lucie and Caloosahatchee Estuaries, and move more water south for agricultural, urban and ecosystem uses. According to agency reports synthesized by Graham et al. (2015), approximately 200,000 acre-feet (acre-ft) of storage is required in the St. Lucie Watershed, approximately 400,000 acre-ft of storage is required in the Caloosahatchee Watershed, and at least one million acre-ft of storage is required in some combination north and/or south of Lake Okeechobee. In spite of these recognized needs, only 40,000 acre-ft of storage is under construction in the St. Lucie Basin (estimated completion 2020), only 170,000 acre-ft is under construction in the Caloosahatchee Basin (estimated completion 2022), and a total of 240,000 acre-ft is included in the Post Authorization Change Report to the CEPP south of the lake, but funds for the design and construction of this project have not yet been appropriated. Furthermore, without reductions in nutrient loading to Lake Okeechobee, water released from the lake will likely continue to cause water-quality-driven adverse impacts to the ecosystems that receive lake discharges. **Only incremental changes in the operation of the South Florida Water Management System can be expected with the limited infrastructure scheduled to be operational and included within the next LOSOM, unless new performance measures are adopted and/or changes are made in the way tradeoffs are assessed among performance measures for water supply, flood control and environmental protection.** In view of these constraints, expectations regarding changes in operational outcomes that will result from the next LOSOM should be communicated to the public clearly and transparently.

In general, the projects required to store and treat water are delayed because of a lack of funding. In the interim, the coupled human-natural system continues to degrade in ways that may be irreversible. **Increased and sustained State and Federal funding to provide additional water**

storage and treatment is critical before the system becomes so degraded that the damage cannot be reversed. In addition, increased research, monitoring and assessment of the system's performance are essential to provide a basis for improved planning of regulation schedules, guide operations, evaluate effectiveness of projects, and detect and adapt to unforeseen events.

Recommendations for the Development of the New Lake Okeechobee System Operating Manual

After extensive interviews with experts and review of available technical reports and peer-reviewed literature, the Technical Review Team identified a number of factors that should be taken into consideration during the development of future LOSOMs. Some of these recommendations are immediately actionable and should be adopted in the current phase of LOSOM planning. Others may require additional research and monitoring prior to implementation. Investment in new research and monitoring should begin as soon as possible so that enhanced knowledge gained through these activities can be incorporated in future phases of LOSOM planning. Technical Review Team recommendations are summarized below:

1. **Water quality and water quantity should be managed together in both LOSOM planning and LOSOM operations, acknowledging that nutrient limitation of primary production may differ in Lake Okeechobee, the Northern Estuaries, Everglades Protection Area and Southern Estuaries.**

    - Improving water quality is essential to achieve the congressionally authorized purposes of the Comprehensive Everglades Restoration Plan (CERP) to restore, preserve, and protect the south Florida ecosystem. Previous ecologic performance measures for the northern estuaries were heavily focused on effects of water quantity, through ecological impacts of lake discharges on estuarine salinity. Future performance measures should also take into account how nitrogen, phosphorus and algae within lake discharge water affect estuarine ecology.
    - A nitrogen control strategy for the northern estuaries, analogous to Restoration Strategies for the EPA and Southern Estuaries, should be developed. This strategy could include: establishing a nitrogen Total Maximum Daily Load (TMDL) and Basin Management Action Plan (BMAP) for Lake Okeechobee; investigating ways to increase *in-situ* denitrification in Lake Okeechobee; building stormwater treatment areas east and west of the lake to remove nitrogen before water is discharged to the estuaries; and/or developing and implementing new nitrogen-based performance measures for the Estuaries.

2. **Improved data and predictive tools are needed to better couple management of hydrology to water quality and ecological impacts in LOSOM planning and operations.**

Data Recommendations:

- Lake Okeechobee sampling protocols that have sufficiently high spatial and temporal resolution to improve understanding of the connection between hydrologic and ecologic conditions in the lake should be designed and implemented. These protocols should include water column physical/chemical variables, algae and cyanobacteria, submerged aquatic vegetation (SAV), emergent plants, fish, and birds. Conditions that precede and trigger in-lake and in-estuary cyanobacteria blooms should be identified, to determine whether water releases can be timed to avoid/prevent bloom events or reduce their intensity.
- The current spatial distribution and stratigraphic characteristics (grain size, density, nutrient forms) of sediment in the mud zone of Lake Okeechobee should be assessed to better understand and model sediment resuspension, determine if resuspended surface muds are a source or sink of phosphorus (P) to the water column, and re-evaluate the relative contribution of allochthonous and autochthonous P loading to the lake.
- Techniques for collecting, processing and measuring samples for the toxin microcystin should be standardized. Studies should be conducted to determine whether all *Microcystis* strains produce toxin, and to determine the causes of microcystin release.
- Additional studies should be undertaken to determine whether cyanobacteria in the St. Lucie and Caloosahatchee Estuaries are regularly “seeded” by existing blooms in the lake or are simply a consequence of high nutrient discharge and sufficient water residence time in the receiving waters.
- Robust monitoring programs to assess not only the state of the estuaries, but also to project their future status, should be designed and implemented. The current set of monitoring sites for the state of seagrasses, oysters and *Vallisneria* should be spatially augmented and monitored more frequently. In-situ water quality and HAB pigment sensors should be deployed and telemetered from sentinel sites. Explicit ecological indicators that are predictive of the trajectory of ecosystem health should be developed for the estuaries, and these predictions should be used in both planning and operations of the Lake Okeechobee system.

Predictive Tool Recommendations:

- The SFWMD has developed promising hydrodynamic, water quality and ecologic modeling tools for Lake Okeechobee and the northern estuaries (e.g., the Lake Okeechobee Environmental Model (LOEM); Hydrologic Simulation Program Fortran (HSPF) and Curvilinear-grid Hydrodynamics model in three-dimensions (CH3D) for the

Caloosahatchee Watershed and Estuary; Wash123 and CH3D for the St Lucie Watershed and Estuary; and Habitat Suitability Index (HSI) models for both estuaries). These models could be used in concert with the South Florida Water Management Model and/or the Regional Simulation Model to link water quality and ecological outcomes to hydrology and water management decisions in a more rigorous, quantitative manner. Accelerated investment in these modeling tools is recommended so that they become an integral part of the planning and operations decision-making toolbox. These linked hydrologic-water quality-ecologic modeling systems could be used in the LOSOM planning process to screen alternative operating plans. They also could be used to broaden monthly analyses of operational conditions that currently include forecasts of climate and hydrologic conditions, to also incorporate forecasts of water quality and ecologic conditions in the lake and estuaries.

- Remote sensing and *in situ* observations should be integrated with predictive models to forecast the onset and demise of *Microcystis* blooms in both Lake Okeechobee and the northern estuaries in near real time. These models could be used to help manage water releases from the lake to the estuaries.

3. **Water quality and ecological antecedent conditions and forecasts should be incorporated quantitatively into LOSOM release guidance flowcharts, along with antecedent conditions and forecasts of climate and hydrology. This approach would represent tradeoffs more transparently and quantitatively when flexible decision-making is exercised.**

- LORS2008 includes release guidance flowcharts that use climate and hydrologic conditions and forecasts to set allowable ranges for Lake Okeechobee releases to the water conservation areas and estuaries. Substantial flexibility exists within these ranges. A retrospective assessment of historical versus simulated lake levels should be conducted for the entire time period since LORS2008 was implemented, to understand the extent to which actual operations deviated from planned and/or modeled operations as a consequence of operational flexibility. If such deviations are large, operational flexibility within LOSOM release guidance flowcharts should be simulated in the planning process to evaluate whether incorporating this flexibility negates differences among alternative regulation schedules.
- Under LORS2008, water quality and ecological conditions that may influence operational flexibility are discussed in weekly conference calls among agency scientists and stakeholders. The improved data and predictive tools described above could be used to incorporate water quality and ecological conditions and forecasts more quantitatively into LOSOM release guidance flowcharts, when dike safety is not a concern. Examples of

water quality and ecological criteria that could be incorporated into LOSOM estuary release guidance flowcharts include: 1) limit lake discharges into estuaries when *Microcystis* concentrations exceed certain limits at lake outflow structures to prevent seeding algal blooms in the estuaries; 2) limit lake discharges into estuaries when total nitrogen (TN) concentrations exceed certain limits to prevent and/or mitigate eutrophication and algal blooms in the estuaries; and 3) manage lake discharges to protect endangered, commercially important and/or recreationally important species in the estuaries.

4. The data used to drive LOSOM planning models should be expanded to include more Atlantic Multidecadal Oscillation/El Niño Southern Oscillation variability, hurricanes, droughts, and other extreme events, as well as near-term projections of climate and sea level rise.

- The climate data used in LOSOM water quantity-quality-ecological planning models should be expanded to include more Atlantic Multidecadal Oscillation (AMO)/El Niño Southern Oscillation (ENSO) variability, hurricanes, droughts and other extreme events. This could be accomplished by leveraging information from long-term, historical (~1915-present) weather data, by generating synthetic realizations representative of historic data, and/or by using projected climate data for the 2025-2050 period.
- Sea level rise scenarios corresponding to the high U.S. Army Corps of Engineers (USACE) projection for 2035 should be used in LOSOM planning to evaluate the robustness of structure operations, flood control, water supply (saltwater intrusion) and estuary salinity envelope performance measures for the proposed alternative plans.
- For each LOSOM alternative, the response of hydrologic-water quality-ecosystem performance measures to expanded climate and sea level rise data, should be evaluated using climate stress tests or scenario discovery analyses. This work should include analysis of performance over the entire expanded historic climate sequence, over subsets of decadal wet or dry periods that may occur during the next LOSOM, and under projected climate change/sea level rise conditions for the 2025-2050 time period.
- The sensitivity of all performance measures to climate variability, climate change and sea level rise should be considered. This effort should include evaluation of the temporal trends of performance measures over projected climate and sea level rise scenarios, in addition to summary statistics over decadal climate sequences and the entire period of historical record.

5. **Improved performance measures, tradeoff analyses and decision-making frameworks should be explored for the next phase of LOSOM planning and future LOSOM schedules.**

    - Simplified, event-based, hydrologic surrogates for lake and estuarine ecological performance measures used in LORS2008 planning should be enhanced. The improved data and predictive tools described above should be used to develop more sophisticated hydrologic measures that better incorporate: antecedent hydrologic/ecologic conditions; the timing, duration, frequency and return interval of events; differences in the resilience of ecosystem components; and a changing climate.
    - Improved economic models and analysis of economic performance measures for all system objectives (e.g., water supply, flood control, navigation, ecological restoration/protection, human health, tourism and real estate values) are needed to help analyze tradeoffs more quantitatively and transparently.
    - All hydrologic, ecologic and economic performance measures should be compared systematically to observed/historic hydrologic, ecologic and economic impacts to quantitatively assess whether ecologic and economic harm is actually experienced when performance measures are not achieved.
    - A multi-objective optimization framework that considers equal, temporally constant weights for all system objectives (e.g., water supply, flood control, lake ecology, estuarine ecology, ecology of the Everglades Protection Area, etc.) may produce inferior results. Other approaches that systematically vary objective weights based on antecedent conditions and variable resilience among system components (e.g., agricultural and urban sectors, tourism, real estate, human health, lake ecology, estuarine ecology, stormwater treatment area (STA) performance, and WCA ecology) may yield better overall long-term system performance.
    - An outreach program to inform the public of the constraints associated with decisions to release water should be developed and implemented. This program should acknowledge that both external and internal nutrient loads are likely to remain high during implementation of the next LOSOM leading to future cyanobacterial blooms and constraints on the amount of water that can be released southward. It should be made clear that decisions to release water always involve trade-offs that result in “winners and losers,” but all stakeholders interests will be considered as quantitatively and transparently as possible.

I. Introduction

Background, Limitations and Constraints

An extensive network of man-made canals, levees and water control structures permeates the south Florida landscape. The land has been ditched, drained and otherwise reconfigured to provide flood protection and fresh water for a current population of more than eight million residents, while simultaneously serving the needs of a multi-billion-dollar agricultural industry (Hodges et al. 2014). Major projects in south Florida include the Herbert Hoover Dike (HHD) around Lake Okeechobee, which was initiated in 1930, and the massive Central and Southern Florida (C&SF) Project, begun in 1948. From an engineering perspective, this regional water distribution and delivery system is highly effective at meeting its intended purposes. Improved human welfare and economic prosperity are tangible consequences of these large projects, targeted mainly at improving flood control and water supply. The water supply and flood control functions of the C&SF continue to be of critical importance to south Florida. The originally authorized C&SF Project also provided for conservation of natural resources, particularly the preservation of fish and wildlife. In this regard, however, the C&SF Project has underperformed, and in fact, has resulted in considerable ecological decline over time.

It is now widely recognized that the flood control and water delivery system that serves Florida's human population and agricultural interests has substantially and adversely impacted natural ecosystems in south Florida, including the St. Lucie and Caloosahatchee Estuaries, Lake Okeechobee and the Everglades Protection Area (EPA), which includes the Water Conservation Areas (WCAs), Everglades National Park (ENP) and Florida Bay (Figure I-1). The environmental problems stem from periods when there is too much water, periods when there is too little water, and a regional delivery system that quickly transports nutrients and other pollutants from upstream agricultural and urban sources to natural systems, where adverse impacts occur. When south Florida receives a large amount of rainfall, there are often damaging freshwater discharges to both east coast and west coast estuaries, whereas prolonged drought strains the capacity of the regional system to deliver sufficient water to its full complement of end-users. During times of high rainfall, especially rains following droughts, nutrients are flushed from soils and wetlands into Lake Okeechobee, the estuaries and the EPA. Yet, except for the periods of highest rainfall, much of the EPA, including the ENP, remains chronically deprived of the freshwater necessary to sustain remnant habitats and native biota.

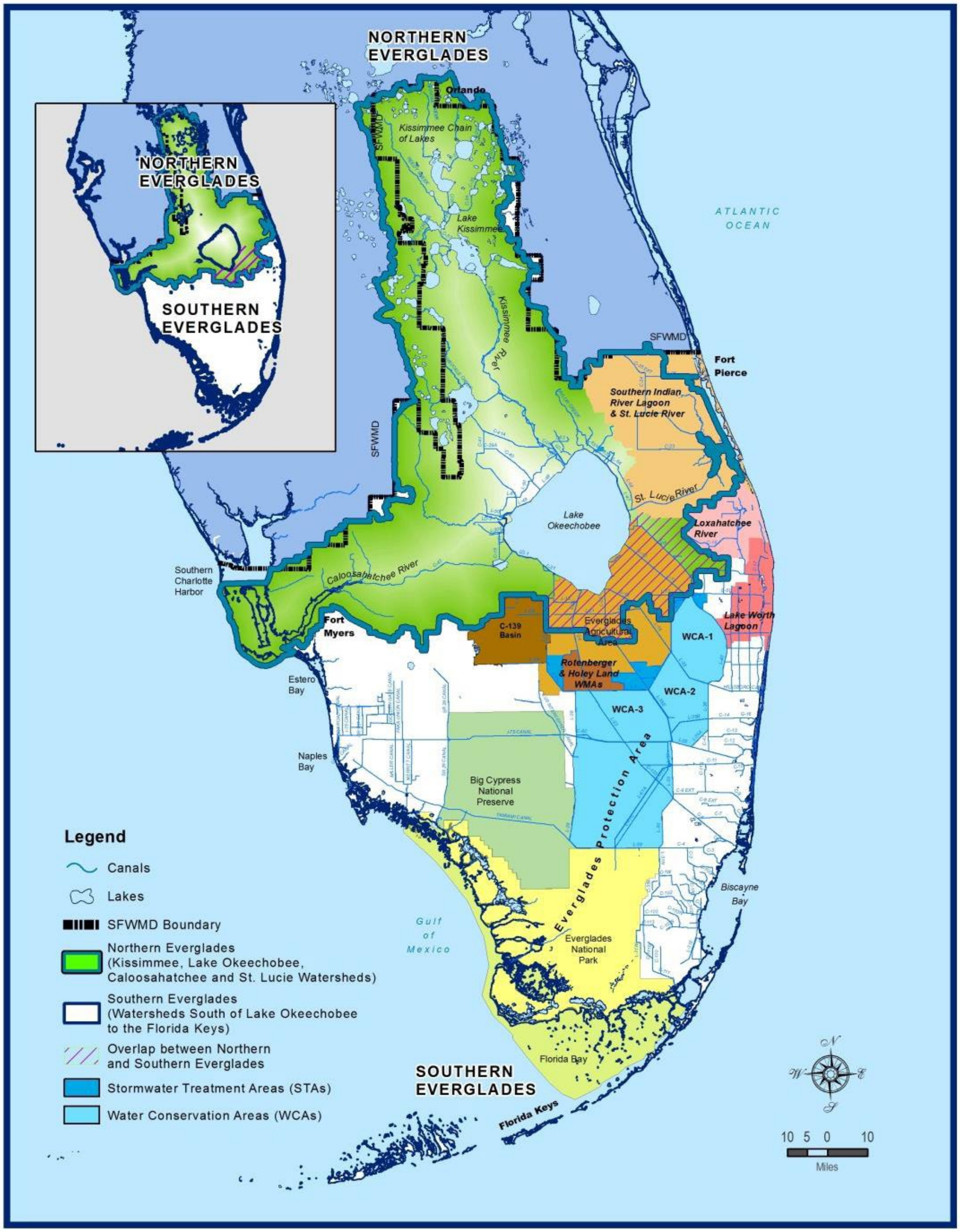


Figure I-1. Map of the Greater Everglades Ecosystem showing the extent of the Northern Everglades, Southern Everglades, Everglades Agricultural Area (EAA), Everglades Protection Area (EPA) and Water Conservation Areas (WCAs) (SFWMD 2019).

Reducing the frequency and duration of damaging freshwater discharges with associated dissolved color, suspended sediment and nutrients to the St. Lucie and Caloosahatchee Estuaries, while at the same time increasing the flow of water south through the Everglades and into Florida Bay, is a challenging task. In the system's pre-engineered state, during high-water events, the vast majority of water that entered Lake Okeechobee overflowed the southern rim of the lake and was carried south into the Everglades as sheet flow. However, urban and suburban development along the eastern and western margins of the historic Everglades, and conversion of marshland into agricultural production south of Lake Okeechobee in what is now the Everglades Agricultural Area (EAA), reduced the Everglades to approximately half its original size. As a consequence, the volume of water that can flow out of Lake Okeechobee to the south, without causing harm to agricultural or urban/suburban areas, has been reduced substantially.

A number of additional constraints limit the amount and timing of water that can be discharged to the south from Lake Okeechobee. These constraints include the much larger capacity of canals and structures that provide inflow to the lake, compared to those that provide outflow; much smaller capacity of outflow canals and structures to carry water south of Lake Okeechobee, versus east and west; flood risks in agricultural and urban areas; legal limits for phosphorus loading to the EPA and ENP; and regulation schedules for the WCAs in the EPA, intended to protect ridge, slough and tree island mosaics and wildlife. Similar constraints based on water quality, nutrient loading and wildlife protection for the northern estuaries do not exist. As a result, these northern estuaries have been used as the primary safety valves for releasing water from Lake Okeechobee.

Repeated planning exercises have shown that large volumes of inter-annual storage and associated water treatment are required north, south, east and west of Lake Okeechobee to manage Lake Okeechobee levels within a desirable range, reduce damage from high and low flows to the St. Lucie and Caloosahatchee Estuaries, and move more water south for agricultural, urban and ecosystem uses. According to agency reports synthesized by Graham et al. (2015), approximately 200,000 acre-ft of storage is required in the St. Lucie Watershed, approximately 400,000 acre-ft of storage is required in the Caloosahatchee Watershed, and at least one million acre-ft of storage is required in some combination north and/or south of Lake Okeechobee. Despite these recognized needs, only 40,000 acre-ft of storage is under construction in the St. Lucie Basin (estimated completion 2020) and only 170,000 acre-ft is under construction in the Caloosahatchee Basin (estimated completion 2022). A total of 240,000 acre-ft is also included in the Post Authorization Change to the Central Everglades Planning Project (CEPP) south of the lake. That project has been authorized, but funds have not yet been appropriated for design and construction.

In 2018, after a particularly wet season in the region, large regulatory discharges from Lake Okeechobee to the St. Lucie and Caloosahatchee Estuaries, and damaging blue-green algae (cyanobacteria) blooms in the lake and both estuaries, raised concerns again about the timing and completion of the Central Everglades Restoration Plan (CERP) and other restoration projects. Interest focused on how changes in the Lake Okeechobee Regulation Schedule might reduce damaging freshwater releases to the estuaries and send more water south to the Everglades, with the new infrastructure expected to be operational in the near future. It should be noted, however, that only incremental changes in the operation of the South Florida Water Management System can be expected, given the limited infrastructure scheduled to be operational and included within the next LOSOM, unless new performance measures are adopted and/or changes are made in the way tradeoffs are assessed among performance measures for water supply, flood control and environmental protection. Therefore, expectations regarding changes in operational outcomes resulting from the next Lake Okeechobee Regulation Schedule should be communicated to the public clearly and transparently.

Description of the Current Lake Okeechobee Regulation Schedule (LORS2008)

The current Lake Okeechobee Regulation Schedule, LORS2008, is a collection of complex operating rules, described in the Water Control Plan (WCP) and the Final Supplemental Environmental Impact Statement (SEIS) published in 2007. It was based largely on the previous schedule, known as the Water Supply and Environment schedule (WSE), but was modified to address concerns regarding the structural integrity of the Herbert Hoover Dike (HHD) that were raised as a result of wet summers during 2003-2005. One major difference between LORS2008 and the earlier schedule was the aim of LORS2008 to hold Lake Okeechobee at a lower level to reduce potential impacts to the integrity of the HHD. Because the management of lake water level requires balancing competing objectives associated with flood protection, water supply, navigation, and preservation of fish and wildlife resources, lowering high lake levels to enhance safety of the HHD has consequences for other objectives. For example, to maintain lower lake levels may require higher discharges to the northern estuaries if water cannot be moved southward because of flooding or water-quality concerns in the EPA.

During the planning phase of the LORS2008 regulation schedule, numerous performance metrics tied to the multiple management objectives were used to evaluate alternative schedules, using hydrologic modeling based on data from the 1965-2000 period of simulation. A preferred alternative was selected that represented the “best operational compromise” for maintaining the environmental health of the major components of the C&SF ecosystems and addressing the safety issue of the HHD and other objectives, such as water supply. Balancing the objectives of operation of the Lake Okeechobee system through the use of performance metrics has been a key approach used in the planning phase of all previous regulation schedules (Trimble and

Marban 1988). However, what led to the LORS2008 schedule being considered the "best" compromise appears somewhat subjective because the relative values of all possible management impacts are not defined explicitly in the planning documents.

The preferred alternative for LORS2008 included four parts to provide water-release guidance based on desired seasonal patterns in water depth in Lake Okeechobee (Figure I-2). Part A shows the three operational ranges: (a) High Lake Management Band; (b) Operational Band; and (c) Water Shortage Management Band. In Part B, the Operational Band is further subdivided into five sub-bands, namely (a) High; (b) Intermediate; (c) Low; (d) Base Flow; and (e) Beneficial Use. Lake releases for maintaining flood protection are generally made in the Operational Sub-band and the High-Lake Management Band and they increase with increasing lake level. In the Water Shortage Management Band, water supply restrictions may be imposed according to Water Shortage Rules outlined in the State of Florida Chapter 40E-21 of the Florida Administrative Code. However, water supply releases may be made in any band in LORS2008. The schedule also includes Parts C and D to provide additional guidance for releases to Water Conservation Areas (WCAs) and Estuaries (Tide) and they are generally known as release guidance flowcharts (Figure I-2). Inclusion of the release guidance flowcharts, which include climate forecasts and outlooks in both WSE and LORS2008 in the Water Control Plan (WCP), represented a major advancement in regulation of large lakes such as Lake Okeechobee.

Under normal conditions, Parts A through D of LORS2008 (Figure I-2) produce a range of allowable lake releases. Additional considerations include occasional release guidance known as Adaptive Protocols (AP) (SFWMD 2010), which may be used by the South Florida Water Management District (SFWMD) to consider baseflow and environmental water supply. The weekly decision-making process includes (a) Tuesday conference calls among the scientists to gather input from all agencies, stakeholders and the public; (b) a Wednesday conference call among the U.S. Army Corps of Engineers (USACE) and SFWMD Water Managers; (c) a recommendation by SFWMD to the USACE; and (d) a recommendation by USACE to its leadership. The final decision by the USACE leadership is implemented for the following 7-day period, and this weekly process is repeated.

Technical Review Team Study Objectives and Approach

In 2019 the SFWMD authorized the University of Florida (UF) to coordinate an independent technical review of the scientific literature and data to inform the development of the next Lake Okeechobee System Operating Manual (LOSOM). Specifically, the UF Water Institute was charged with constituting an interdisciplinary team of experts to synthesize existing knowledge and data, identify knowledge gaps, and present recommendations to guide the development of the new LOSOM.

After extensive interviews with experts and review of available technical reports and peer-reviewed literature, the Technical Review Team identified a number of factors that should be taken into consideration during the development of future LOSOMs. Section II presents a synthesis of knowledge and data gaps regarding the impacts of the lake levels on the ecology of Lake Okeechobee. Section III presents a synthesis of knowledge and data gaps regarding the impacts of the Lake Okeechobee discharges on the ecology of the St. Lucie and Caloosahatchee Estuaries. Section IV presents opportunities for incorporating new climate and sea level information into the Lake Okeechobee Regulation Schedule, and Section V summarizes improvements in performance measures, tradeoff evaluation and decision-making that should be considered in the development of future lake regulation schedules. It should be noted that some Technical Review Team recommendations are immediately actionable and should be adopted in the current phase of LOSOM planning. Others may require additional research and monitoring prior to implementation. Investment in new research and monitoring should begin as soon as possible so that enhanced knowledge gained through these activities can be incorporated in future phases of LOSOM planning.

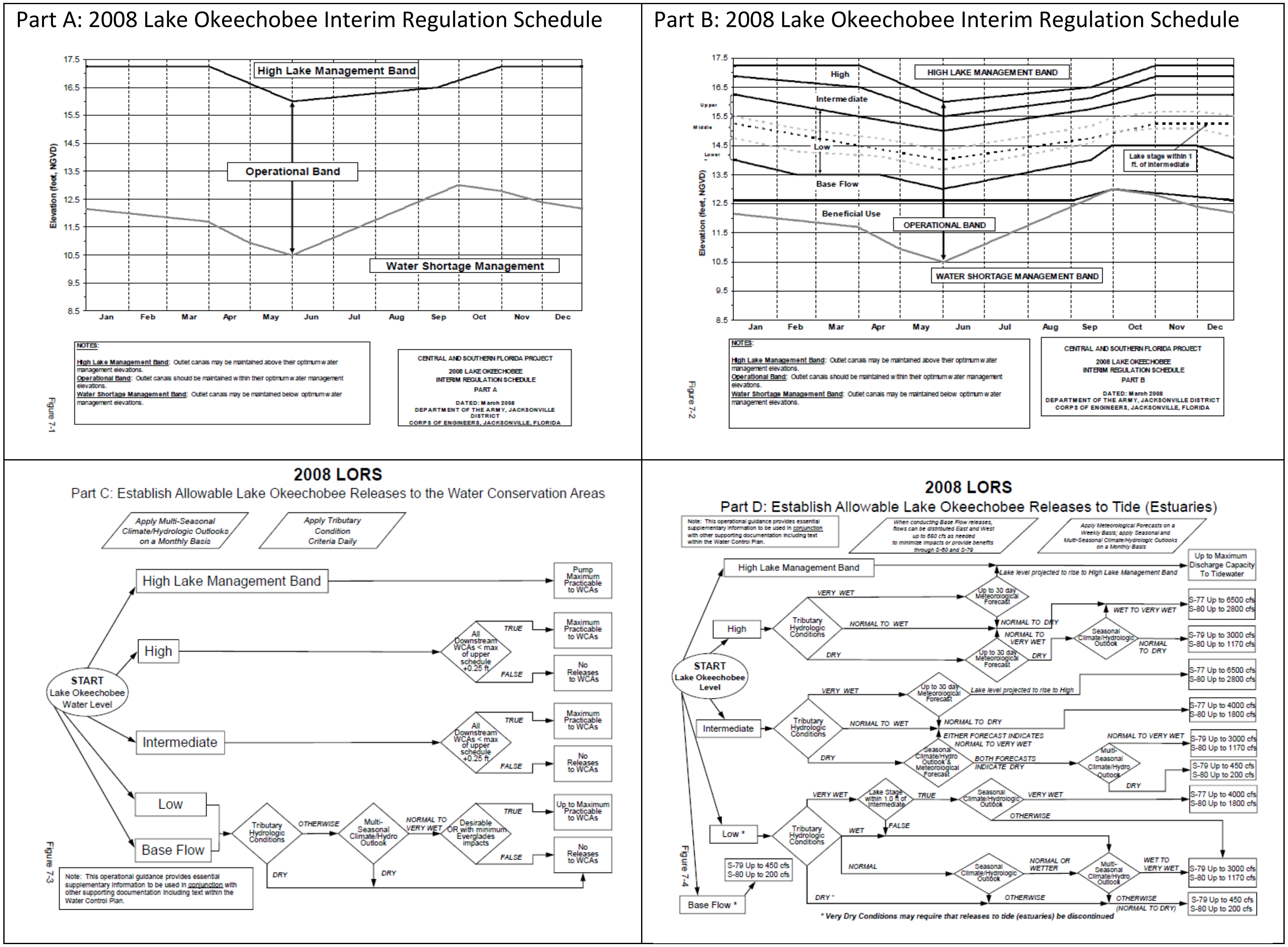


Figure I-2. Parts A through D of LORS2008.

II. Impacts of Lake Levels on the Ecology of Lake Okeechobee

Introduction

The C&SF Project was designed with Lake Okeechobee serving as the central water storage area. Unlike most flood-control reservoirs, Lake Okeechobee currently lacks a natural outflow that would enable rapid discharge of water when lake stage is high enough to potentially compromise the structural integrity of the surrounding levee. With the current infrastructure, hydrologic inputs to Lake Okeechobee may exceed outputs by a factor of 4-6 depending on rainfall, antecedent conditions in the drainage basin to the north, and water level in the lake. If substantial rain falls north of the lake, large inflows to the water body can quickly raise the lake level by several feet, thereby putting the levee at risk. Under such high-stage scenarios, water is released from the lake to avoid potential catastrophic flooding (USACE 2008). However, such water releases are highly constrained by many factors, including a lack of infrastructure that can move large volumes of water southward, the inability of the Water Conservation Areas south of the lake to receive substantial inflows without negative ecosystem impacts or flooding risks, and Federal regulations that restrict the amount of phosphorus-rich water that can be delivered to the Everglades. Consequently, canals east and west of the lake, which lead to the St. Lucie and Caloosahatchee Estuaries, respectively, are the main conduits for rapid removal of water from Lake Okeechobee when stage is deemed to be too high.

Lake Okeechobee Regulation Schedules must balance competing objectives associated with flood protection, water supply, navigation, and preservation of fish and wildlife resources in the lake, estuaries and Everglades Protection Area (EPA). In Lake Okeechobee protracted periods of high stage have been shown to have deleterious effects on the littoral zone and plankton dynamics (e.g., increased potential for harmful algal blooms). Conversely, high frequencies, magnitudes and durations of low lake levels compromise water and wildlife resources within the lake, as well as navigation. The 2008 Lake Okeechobee Regulation Schedule (LORS2008) specified a stage envelope that targeted lake levels between 12.5 and 15.5 ft to protect both Lake Okeechobee ecology and the integrity of the Herbert Hoover Dike (HHD). Recent reinforcement of the HHD may enable greater future storage within the lake, i.e., higher lake stage, without the threat of dike failure, perhaps enabling greater flexibility in operations. Such an increase in water level, however, has potential ecological implications for the lake.

Performance measures intended to protect Lake Okeechobee ecology could be improved by conducting more rigorous assessments of the relation between aspects of hydrology (flow, lake stage, water residence time, antecedent conditions, and rate of water-level fluctuation) and in-lake ecological conditions, e.g., nutrient (N, P) concentrations, algae and cyanobacteria densities, total suspended solids concentrations, light penetration, distribution and abundance of submerged aquatic vegetation (SAV) and emergent plants, and health of sportfish, wading bird and snail kite populations. Ideally, process-based and/or statistical models of water quality and the lake's ecology should be combined with hydrologic models in planning and operation of the Lake Okeechobee System Operating Manual (LOSOM). This approach would enable water quality and ecological antecedent conditions and forecasts to be incorporated quantitatively into LOSOM release guidance flowcharts, along with climate and hydrologic conditions and forecasts.

Successful integration of quantitative ecological information about the health of Lake Okeechobee into LOSOM release guidance flowcharts will require a solid understanding of the complex relationships between hydrology and ecology, with the full realization that such relationships are likely non-linear, especially at extreme (high/low) lake levels, and are affected by both antecedent hydrologic (e.g., duration of high/low stages) and ecological conditions (e.g., SAV abundance and health status). Determination of relationships between lake stage and biotic conditions is also complicated by different response times to changing hydrology among different components of the biota. Relationships between hydrology and ecology can be assessed by exploring existing historical hydrologic and biological data, but successful management also will require consistent monitoring of lake and estuarine conditions at high spatial and temporal resolution, not only where and when things "go bad." Going forward, it also will be advisable to consider how climate variability and change might influence decisions regarding water releases. The amount and timing of rainfall within years, and over multiple years, has the potential to affect multiple biotic communities within the lake. Even modest changes in temperature, relative humidity and wind speed may affect the system hydrology by altering lake evaporation and changing rates of evapotranspiration in the vast littoral zone.

To explore how quantitative relationships between hydrology and ecology could lead to improved lake performance measures for the new LOSOM, the Technical Review Team 1) explored established relationships between lake hydrology and ecology; 2) identified gaps in knowledge that should be filled to better manage the ecology of the broader Lake Okeechobee/Estuaries system; and 3) identified data that should be collected to improve understanding of responses of aquatic biota to shifts in lake hydrology. The Team acknowledges at the outset that decisions concerning water releases from Lake Okeechobee, even those based on solid information regarding ecological conditions in the lake and receiving waters, are highly constrained by the limited water storage capacity of the lake itself and the fact that nutrient loading to the lake continues relatively unabated. Decisions regarding planning and operation of Lake Okeechobee hydrology will involve compromises. All stakeholders will not be pleased with all decisions, but trade-offs should be considered carefully in an effort to maintain the environmental integrity of the lake and estuarine ecosystems, provide for public health and safety, and promote socio-economic well-being.

Lake Okeechobee Background

Lake Okeechobee is one component in a series of hydrologically connected aquatic ecosystems that extend from central Florida to the Atlantic and Gulf Coasts of the state, and southward to the Everglades and Florida Bay. The lake occupies a shallow basin, formed by uplift and exposure of ancient sea floor and subsequent hydrologic damming by accumulated peat deposits along the southern shoreline. Similar to most shallow water bodies in Florida, Lake Okeechobee has held water continuously only since the early to middle Holocene, i.e., for the last ~6000 years (Brooks 1974; Donar et al. 2009; Larios et al. 2018). The water body has the distinction of being the largest freshwater lake (~1800 km^2) in the U.S. that is wholly contained within the borders of a single state.

Current hydrological conditions in Lake Okeechobee are largely a consequence of multiple engineering efforts since the early-middle 20th century, designed to prevent flooding and provide for water needs in south Florida, especially during the dry season. Levee construction during the 1930s was a response to the devastating hurricanes of 1926 and 1928, the latter still recognized as one of the deadliest natural disasters in the United States (Will 1961 [1978]). Construction of the Herbert Hoover Dike (HHD) was undertaken to prevent flooding and effectively converted the lake into a massive water storage basin. Today, management of this engineered system is highly constrained, as the needs of multiple stakeholders are often in conflict.

Ecological conditions in the lake are affected on short- and longer-term timescales by multiple factors, including weather/climate, system hydrology, and human land use north of the lake, all of which influence nutrient loads to the water body. Lake ecology concerns are related to issues of water clarity, nutrient concentrations, cyanobacteria blooms, status of SAV, marsh health, the freshwater fishery, wading bird populations, migratory birds, and conservation of animal species of particular concern, such as snail kites, bald eagles and wood storks. Strategies for improving ecological conditions in the lake often conflict with other objectives such as maintaining optimal salinity ranges in the estuaries east and west of the lake required to support oyster populations and seagrasses in the downstream sectors of the estuaries, and freshwater SAV taxa, such as *Vallisneria americana*, in the upstream reaches. Periodic releases of nutrient-rich lake water to the coastal estuaries are blamed for harmful algal blooms, including proliferation of the toxin-producing cyanobacterium *Microcystis*, as well as other negative impacts such as fish kills, loss of oysters and other benthic invertebrates, and demise of seagrass beds. Low lake levels during drought years cause concerns regarding maintenance of sufficient water in the western marsh zone; spread of nuisance plant species; sufficient water delivery to riparian agricultural areas, urban communities, and the Everglades; and maintenance of salinity regimes in connected estuaries that support healthy invertebrate (e.g., oysters), fish and freshwater SAV communities.

Decisions *vis a vis* planning and operations involve consideration of water quantity and quality, as well as the timing of releases, with concerns about quantity (flood prevention and water provisioning) typically trumping quality. Given the multiple competing needs for water and flood protection among natural ecosystems and humans in south Florida, combined with the artificial nature of the plumbed hydrologic system, "restoration" of Lake Okeechobee and connected wetland ecosystems (including the Everglades) to a pre-disturbance or "quasi-natural" state is unrealistic and unachievable. Furthermore, little is known about the pre-disturbance state of the lake ecosystem. A more feasible approach is adoption of strategies to manage the highly modified, "artificial" system to achieve preferred environmental outcomes. With this in mind, knowledge and data gaps about Lake Okeechobee ecology that could better inform decisions regarding water releases and mitigate negative ecological impacts on the lake and on aquatic ecosystems that receive lake water discharges, particularly the coastal estuaries are identified below. Whereas the focus of this section is on Lake Okeechobee ecology, the hydrologic connectivity of central and south Florida aquatic ecosystems makes it imperative that the hydrologic regulation schedule takes a holistic view that considers the environmental consequences of planning and operation beyond the borders of the lake, e.g., for maintenance of macrophyte populations and benthic habitats in downstream estuaries.

Lake Okeechobee Morphometry and Zones

Understanding relationships among Lake Okeechobee water level and in-lake physical and chemical conditions is important for understanding lake ecology. Lake Okeechobee shares morphometric attributes with other big Florida water bodies such as Lakes Istokpoga, Kissimmee and Apopka, in that it has a very large surface area, but is shallow (Brenner et al. 1990). Okeechobee's low relative depth (ratio of maximum depth/mean diameter = ~0.0001) makes it extremely prone to wave-generated sediment resuspension and transport. The lake's long fetch enables wave turbulence to reach the lake bottom, where unconsolidated inorganic and organic components of surface sediments are easily re-suspended into the water column (Havens 2003; Havens et al. 2007; Jin and Sun 2007).

It is clear from studies that identified zones in Lake Okeechobee on the basis of surface sediment type (Fisher et al. 2001, 2005) and/or limnological characteristics (Phlips et al. 1993a), that sediment types are intimately linked to conditions in the overlying water column (Figures II-1, II-2, II-3). Surface sediment types identified by Fisher et al. (2001, 2005) are described here, based on data gathered in 1988 and 1998, and updated in a 2006 study (BEM & University of Florida 2007; Yan and James 2012). Fisher et al. (2001, 2005) distinguished between bottom deposits in the western littoral zone and peats in the southern part of the lake, whereas the follow-up studies included sediments from both of those zones in a single “peat” category, yielding four sediment types (Figure II-1). For this discussion, five categories distinguished by Fisher et al. (2001, 2005) are used to describe the sediment types.

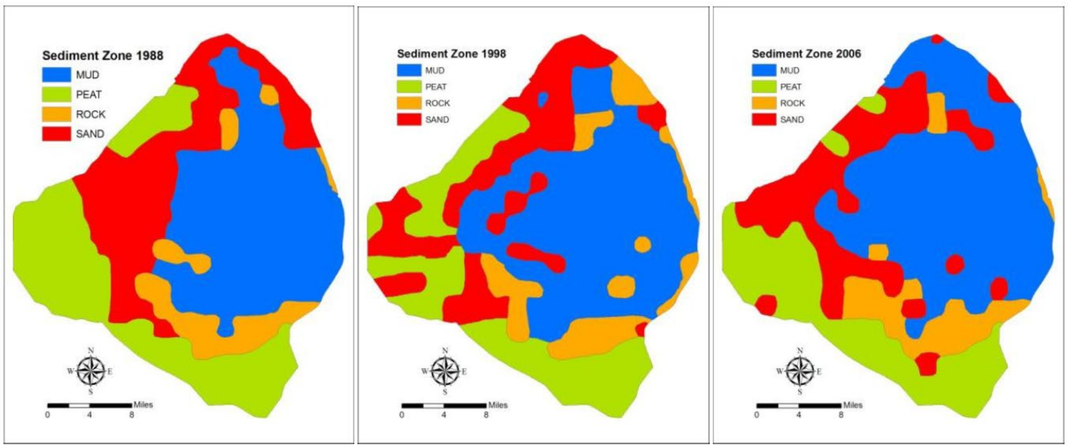


Figure II-1. Map of surface sediment types in Lake Okeechobee, based on sampling in 1988 (left), 1998 (center) and 2006 (right), from Yan and James (2012). Maps of the 1998 and 1998 sediment distributions were modified from Fisher et al. (2005).

The western littoral zone occupies about 18% of the basin area and has water depths of 1 to 3 feet (0.3-1.0 meters (m)). The littoral zone is characterized by abundant aquatic macrophytes of all forms, i.e., emergent, submerged, floating-leaved and floating, as well as dense periphyton. Parts of the littoral zone are completely exposed (sub-aerial) during drought periods. East of the littoral zone lies a broad, north-south-trending zone that is characterized largely by sand bottom. Water depth ranges from about 3 to 6 feet (0.9-1.8 m). Thousands of acres of SAV, including both vascular plants (*Vallisneria*, *Potamogeton*, *Hydrilla*) and benthic macroalgae (*Chara*) can occur along the western fringe of this near-shore zone, typically under shallow, clear-water conditions (Hwang et al. 1999; Havens et al. 2002).

Eastward of the sand-bottom zone is a mud-bottom zone that corresponds to a large, homogenous, open-water area that is relatively flat and has water depths that range from 14 to 16 ft (4.3-4.9 m), depending on lake stage. Surrounding the mud zone is an area of the lake characterized by “rock” bottom. South of the mud zone, the rock bottom consists of an east-west-trending fossil limestone reef that is exposed at low lake stage. Lastly, the southern sector of the basin is characterized by peat sediments.

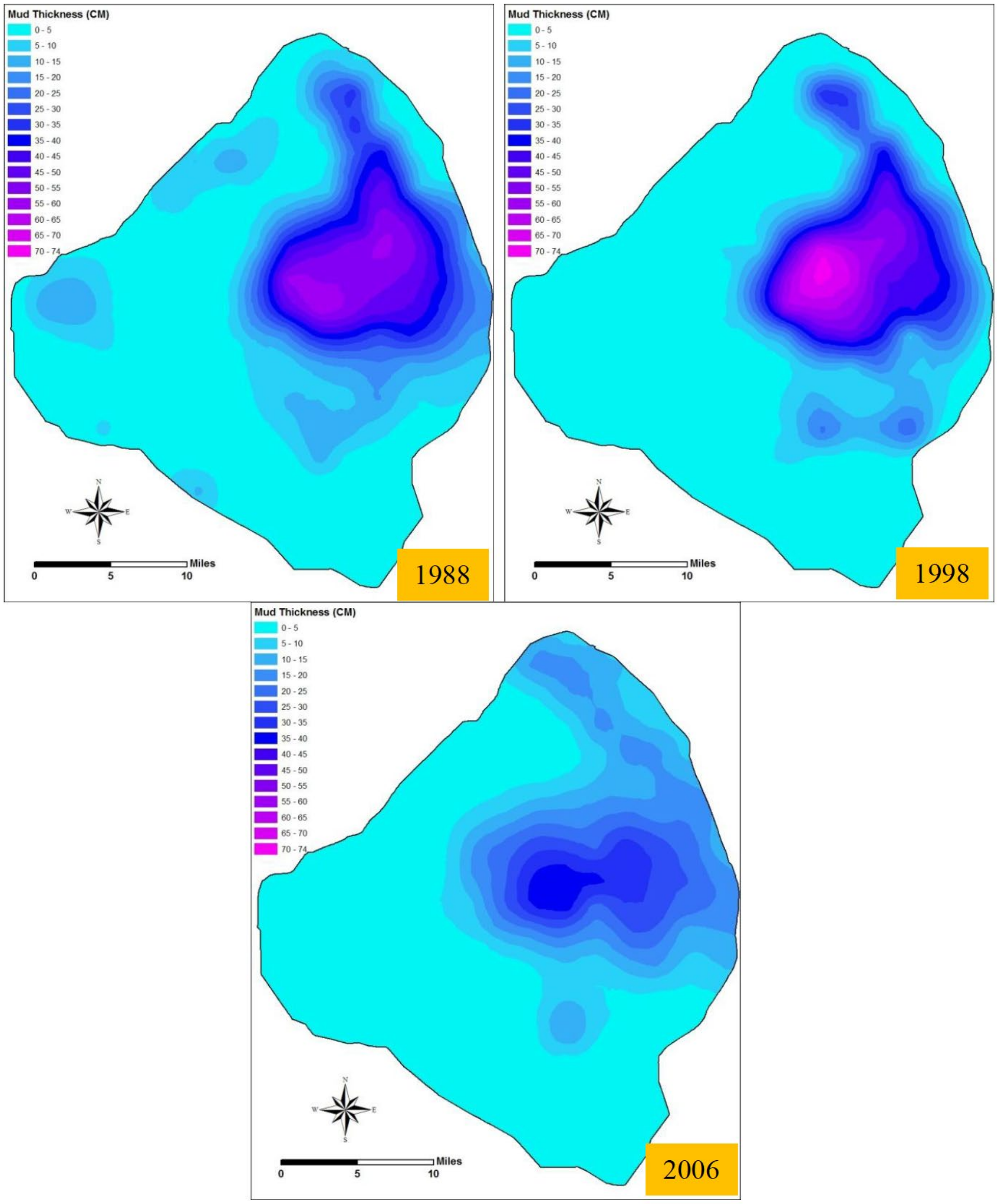


Figure II-2. Sediment thickness (cm) in Lake Okeechobee in 1988, 1998, and 2006 (from Yan and James 2012), illustrating the dynamic nature of the easily suspended mud deposits (James et al. 2008). Data from 2006 were collected after the hurricanes of 2004 and 2005.

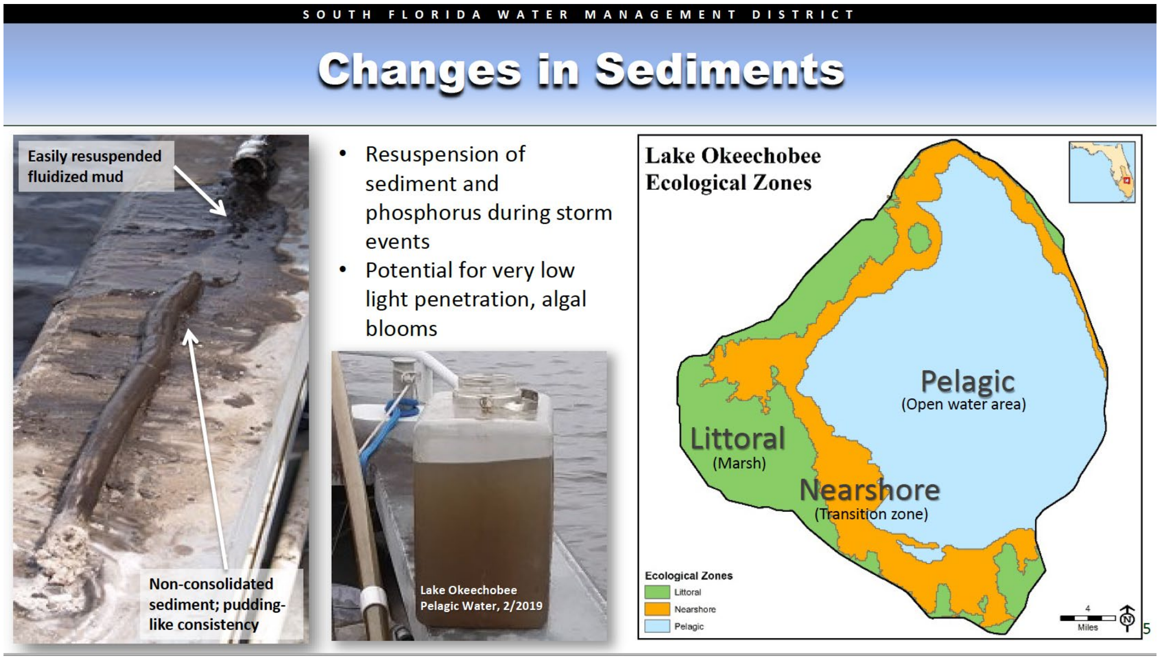


Figure II-3. Slide 5 of the U.S. Army Corps of Engineers (USACE) webinar on *How Lake Okeechobee Water Levels Affect Lake Ecology*, illustrating: 1) the spatial correlation between sediment type and ecological zones in Lake Okeechobee (see Figure II-1); and 2) the importance of mud sediment resuspension on limnological variables, including total phosphorus concentration, total suspended solids concentration, and light attenuation. Prepared by Z. Welch, Applied Sciences Bureau, SFWMD. Webinar last accessed on 30 September 2019 at: https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll11/id/3906

Lake Nutrients and Harmful Algal Blooms

There is utility in describing the lake zones based on sediment type, in that re-suspended sediments from the mud zone affect in-lake water-column conditions profoundly. For instance, re-suspended sediments, i.e., total suspended solids (TSS), attenuate light, thereby affecting SAV negatively and limiting algae production (Phlips et al. 1995, 1997; Havens 2003) (Figure II-4). Furthermore, internal loading of nutrients from sediments is now a substantial source of phosphorus and nitrogen to the water column, and fuels primary production in the lake, in some cases causing harmful algal blooms. Management of excessive nutrients in eutrophic lakes has typically focused exclusively on phosphorus as the driver of such blooms. In recent years, however, there has been growing evidence that controlling nitrogen concentrations is also important, particularly in aquatic ecosystems that are prone to nitrogen limitation of algal growth (Havens 1995). A number of bloom-plagued lakes in Florida have been shown to exhibit periods of nitrogen limitation. These include the state's two largest water bodies, Lake Okeechobee and Lake George. This finding warrants future investigation of potential approaches to control nitrogen loads and influence nitrogen cycling (e.g., denitrification) in these lakes, as ways to prevent harmful algal blooms. Such strategies may be particularly effective for mitigating the bloom intensity of Florida's most prolific toxic blue-green algae species, *Microcystis aeruginosa*, which, unlike some other cyanobacteria species, is not capable of nitrogen fixation, i.e., conversion of nitrogen (N_2) in water into ammonium, for cell growth.

Estimated internal nutrient loads from the sediment to the water column in Lake Okeechobee (Fisher et al. 2005) illustrate the challenges associated with reducing the trophic status of the water body. Estimates of internal Dissolved Reactive Phosphorus (DRP) flux from the sediments to the lake water column were 326 metric tons per year (mt yr^{-1}) in 1989 and 472 mt yr^{-1} in 1999, values comparable to or greater than estimated annual external surface DRP loads, which averaged 316 mt yr^{-1} from 1979 to 1988 and 258 mt yr^{-1} from 1989 to 1999. The estimated internal Dissolved Inorganic Nitrogen (DIN (NH_4-N)) load in 1999 was 4500 mt yr^{-1}, substantially larger than the mean external annual surface load of DIN estimated for the period 1989-1998 (896 mt yr^{-1}). Oxygen demand in the sediment cores was strongly correlated with DRP and DIN flux, indicating that internal nutrient loading results largely from microbial respiration of organic material.

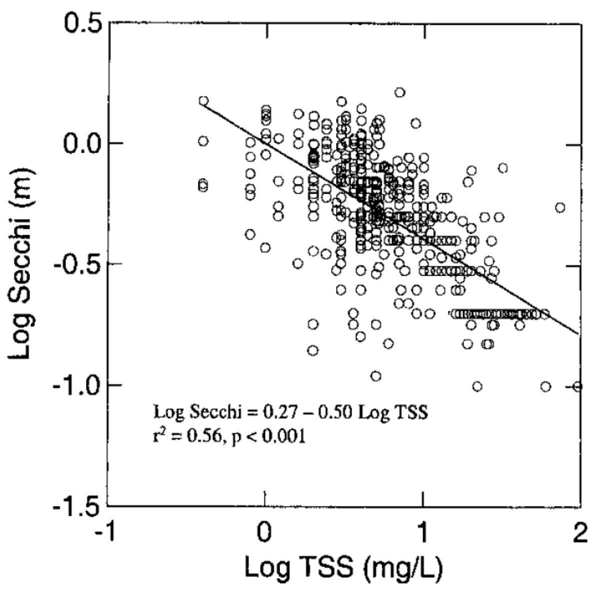


Figure II-4. Negative relationship between log total suspended solids (TSS) and water column transparency (log Secchi disk depth) in the Lake Okeechobee water column. From Havens (2003).

There has been abundant research on nutrient concentrations in Lake Okeechobee waters, and the Total Maximum Daily Load (TMDL) for total phosphorus was set at a level equivalent to 140 metric tons/year with the goal of reducing in-lake total phosphorus (TP) concentrations to ≤ 40 μg/L (Walker and Havens 1995; Havens and Walker 2002), a value that would, nevertheless, still maintain eutrophic conditions in the lake. Annual TP inputs to the lake, however, have typically remained 3-4 times larger than the target value, and consequently, annual water-column TP concentrations have rather consistently averaged > 100 μg/L.

Despite desires to limit external nutrient loads to Lake Okeechobee, legacy anthropogenic phosphorus is abundant in soils north of the lake (Reddy et al. 2011; Dunne et al. 2011), and a number of ongoing land uses (e.g., improved pastures, dairy farming, citrus production, and urban development) continue to supply the lake with phosphorus (P). Dunne et al. (2011) indicated that legacy P in the basin was sufficiently large to supply the lake with ~500 mt/year of TP over the next half century. Delivery of TP to the lake is a function of combined inflow volume and in-stream nutrient concentration. Periods of extreme TP loading to the lake can be associated with high rainfall, given that current water management infrastructure lacks the capability to attenuate higher volumes of runoff (Figure II-5).

Fisher et al. (2005) argued that even if external nutrient reductions could be achieved, diffusive fluxes from the sediment would continue to be substantial sources of DRP and DIN to the lake water column. Internal loading of N and P, which emanates from sediments via diffusive flux, is important in fueling lake primary production (Fisher et al. 2005). Periodic sediment re-suspension events can also play a role in maintaining eutrophic to hyper-eutrophic conditions in the lake (Havens et al. 2007).

Typically, chlorophyll *a* concentration, a proxy for living algae abundance in the water column of lakes, remains lower than might be expected in Lake Okeechobee, given the high TP values (Figure II-6). This deviation from expectation may be attributed to several factors: 1) much of the TP measured in the water column during re-suspension events is not bound in living algae, but rather, is associated with inorganic matter or dead cells in which the chlorophyll *a* has degraded (James et al. 2005); 2) high turbidity reduces light penetration, thereby limiting algal primary production, despite high nutrient concentrations (Aldridge et al. 1995); and 3) the system is often nitrogen-limited (Aldridge et al. 1995; Phlips and Ihnat 1995), a likely consequence of long-term anthropogenic P loading (Havens 1995). Nitrogen-limitation suggests that temporal variability in external nitrogen loads may contribute to defining the relative importance of nitrogen-fixing and non-nitrogen-fixing species of cyanobacteria, as observed in another large Florida water body, Lake George (Nelson et al. 2018).

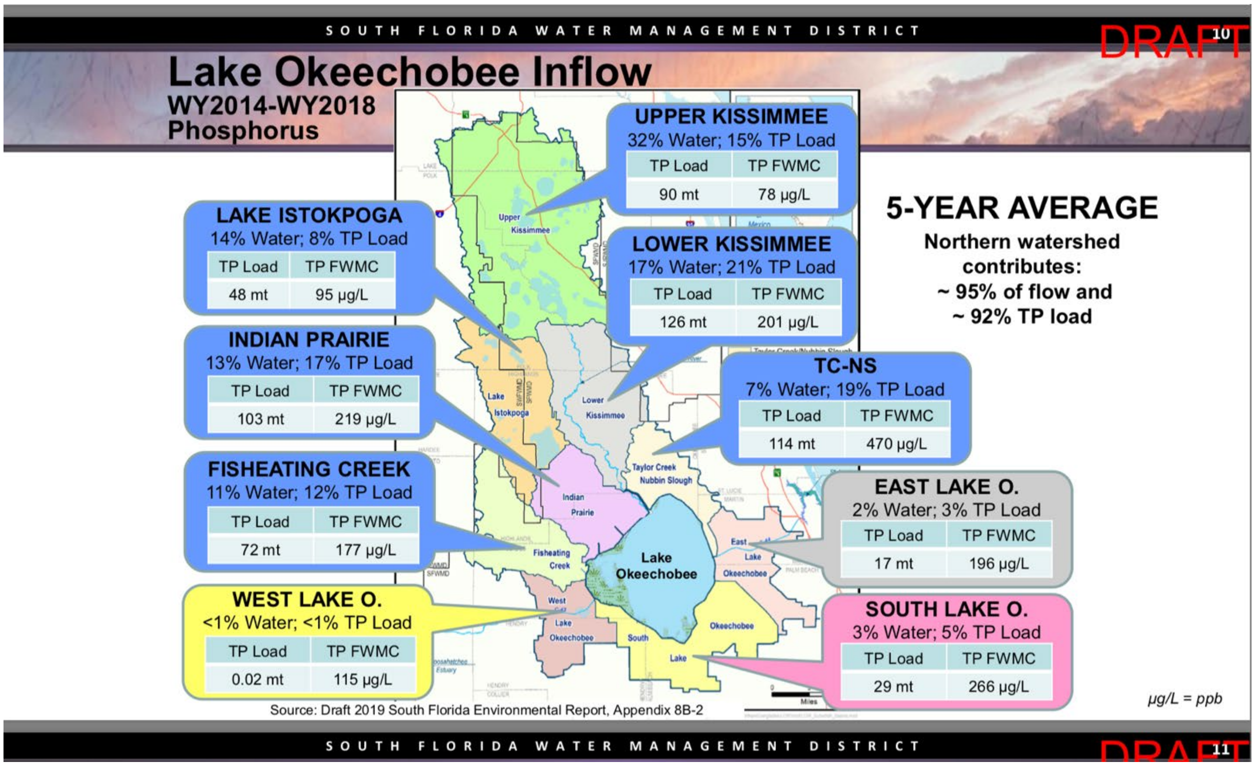


Figure II-5. Hydrologic and total phosphorus inputs to Lake Okeechobee (2014-2018) by sub-basin. Three sub-basins (Indian Prairie, Lower Kissimmee, Taylor Creek-Nubbin Slough [TC-NS]) account for 57% of the P load. Whereas only 7% of the hydrologic input comes from TC-NS, 19% of the P load is derived from that sub-basin (SFWMD Draft Report 2019).

Some of the P that enters Lake Okeechobee makes its way into the littoral zone during high-stage events, and that phosphorus is thought to be responsible for the spread of cattail (*Typha* spp.) in the marsh. One negative consequence of cattail proliferation is that it does not provide suitable habitat for fish or nesting resources for wading birds, as do the plant species it replaces. Invasive torpedo grass (*Panicum repens*) also dominates areas of the marsh, and its dispersal is facilitated by the ability of fragments to remain buoyant for long periods of time and then root and become established when they come in contact with exposed or shallow-water sediment (Smith et al. 2009).

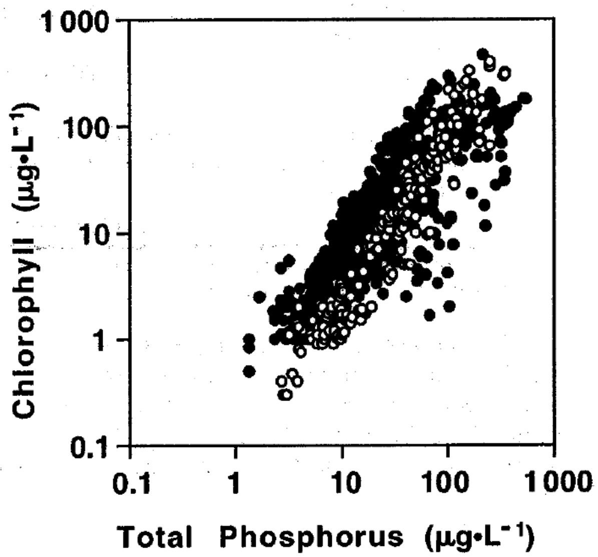


Figure II-6. Average July-August data for temperate lakes (open circles), showing the relation between total P and chlorophyll *a* concentration in the water column (Jones and Bachmann 1976). Solid circles are annual averages based on monthly sampling of Florida lakes. An empirical model relating total P and chlorophyll *a* in Florida lakes is log(chl *a*) = 1.053 log(TP) - 0.369. From Brown et al. (2000).

Sediments and Lake Trophic Status

Questions remain about the role that sediments and internal nutrient loading play in fueling harmful algal blooms and biotic changes in Lake Okeechobee. Pollman and James (2011) suggested that recent sediments have become increasingly saturated with soluble reactive phosphorus (SRP), limiting their ability to adsorb additional available P. They also argued that release of SRP to the water column is related to the dissolution of calcium carbonate in the sediments that is driven by microbial respiration of organic matter, and that during years of high $CaCO_3$ dissolution, consequent internal P releases could exceed external P loads. The authors, however, argued that reducing external loads would eventually reverse the trend in internal loading, as sediment-stored P is released to the water column and transported out of the lake. Nevertheless, lakes north of Okeechobee, e.g., Lake Istokpoga, may also be experiencing SRP saturation of their sediments, implying that such upstream water bodies may become larger net sources of SRP to Okeechobee in the future (Belmont et al. 2009).

Sediment studies (Brezonik and Engstrom 1998; Engstrom et al. 2006; Fisher et al. 2005; BEM & UF 2007), in combination with modeling efforts (Jin and Sun 2007), suggest that organic sediment accumulation in the mud zone of Lake Okeechobee is a relatively recent phenomenon, which accelerated in the latter half of the 20th century. It has also been suggested that unconsolidated surface sediments have shifted location and undergone physical and chemical changes in the past three decades (Yan and James 2012). Although it is clear that sediments represent a long-term P sink, further study will be required to determine if episodic sediment re-suspension is now a short-term source or sink for available nutrients in the water column. Additional investigations are also warranted to assess how lake stage influences sediment re-suspension. Such re-suspended material should be characterized with respect to lithology, particle size and chemical attributes. It will be imperative to determine how episodic resuspension of mud deposits relates to harmful algal blooms.

Although it is well known that unconsolidated surface deposits are easily entrained into the water column of Lake Okeechobee (Ji and Jin 2014), there remains a question as to how deeply wave-generated re-suspension penetrates into the sediments, with some model estimates suggesting values as high as 25 cm, associated with hurricane winds (Jin et al. 2011). Empirical verification of sediment resuspension depth can be achieved by collecting short sediment cores from sites throughout the mud zone and analyzing them at high depth resolution, e.g., centimeter intervals, for density (dry mass/wet volume = g dry/cm^3 wet) during calm, "clear-water" periods. In conjunction with measures of integrated total suspended solids (TSS) in the water column (mg/L) during re-suspension events, which can be converted to TSS per unit area in the water column (g dry/cm^2), it will be possible to estimate how much of the "settled" mud, in terms of depth, is re-suspended by wave turbulence.

Stratigraphic analyses of P forms (SRP, KCl-extractable, NaOH-extractable, HCl-extractable and residual [organic]) in sediment cores should be undertaken to evaluate if the relative abundances of each nutrient form have changed through time (Olila et al. 1995; Fisher et al. 2005). If Pollman and James (2011) are correct about sediments having become saturated with SRP, one would expect to see an up-core rise in the most labile P forms, keeping in mind that down-core stratigraphic changes in chemistry also reflect post-depositional (diagenetic) sediment alteration.

Wind-generated turbulence in the water column diminishes with greater water depth, so intuition suggests that re-suspension should decline with increasing water depth above the mud bottom. But the long fetch of Lake Okeechobee makes most of the fine-grain surficial sediments in the mud zone susceptible to re-suspension, regardless of lake stage (water depth) in this broad, shallow basin (Bachmann et al. 2000). Some negative ecological impacts are associated with the high turbidity that occurs at greater lake stage. It is unlikely that there is a simple relation between lake stage and impact on any single component of the biota, with factors such as duration of high water, weather events, wind speed, time of year, antecedent conditions and health of the biota all influencing the ecological outcomes of high-stage episodes.

High stage does not typically have a negative impact on the open-water, central pelagic zone, i.e., the zone underlain by mud sediments. Harmful algae blooms in this area of the lake are relatively uncommon and related to external nutrient loads under wet conditions, followed by a period of calm weather (Havens et al. 2016).

As might be expected based on the physical limnology of the system, if the lake stage is held at low level, then high winds, large surface waves (wave height being a function of fetch length) and consequent sub-surface turbulence could more readily re-suspend and transport mud-bottom sediments. A subsequent rise in lake stage could then deliver suspended solids to other sectors of the lake, thereby altering nutrient conditions and light penetration. This hypothesis could be tested with the Lake Okeechobee Environmental Model (LOEM) (Ji and Jin 2006), a hydrodynamic wind-wave sediment re-suspension and transport tool of the SFWMD. Further investment in development and validation of this tool is encouraged.

Algal blooms often originate over the sand zone (the area between the mud zone and the western littoral zone), where there is less tripton in the water column and greater light penetration than over the frequently turbid mud zone (Phlips et al. 1995). Much of the sand zone lacks SAV, perhaps because of light attenuation by phytoplankton, suspended tripton, and dissolved color, or because the substrate is not appropriate. It is likely that algae blooms that do originate in the zone are fueled by nutrients that enter the water column from the sediments or are transported into the zone from elsewhere by currents. Whereas light attenuation in the sand zone can limit SAV growth, there is evidently sufficient light for algal proliferation. Algae populations, even under somewhat turbid conditions, may be sustained by turbulence, which periodically circulates the cells throughout the water column. It has been suggested that shallow Florida lakes possess meroplanktonic ("half planktonic") algal taxa that are adapted to settling out of the water column, only to be physically stirred back into the photic zone under windy conditions (Schelske et al. 1995). Such resuspension events may afford these species access to nutrients on or near the lake bottom, as well as periodic exposure to light.

Submerged and Emergent Aquatic Macrophytes and Lake Stage

At the border between the sand zone and littoral zone is the area sometimes populated by abundant SAV (Figure II-7), including both macroalgae (*Chara* spp.) and higher plants (e.g., natives *Vallisneria americana*, *Potamogeton illinoiensis*, and exotic *Hydrilla verticillata*). Such plants and their associated epiphytes represent a substantial sink for nutrients and serve as habitat for a variety of invertebrate species and maturing fish (Havens et al. 2002). This area of the lake displays two alternative states, similar to those described by Scheffer (1989, 2001) for shallow, eutrophic lakes in temperate regions. That is, the zone is characterized by either a clear-water, macrophyte-dominated state, or a turbid, algal-dominated state (Aumen and Wetzel 1995). When submerged macrophytes and their associated epiphytes are abundant, they sequester P rapidly (Hwang et al. 1999), thereby limiting the pool of nutrients available to fuel phytoplankton production. Similar to what occurs in Lake Panasoffkee, north Florida (Brenner et al. 2006), sloughing of the SAV epiphyte load and associated calcium carbonate may be a mechanism by which P is sequestered in Lake Okeechobee sediments, only to be released in association with carbonate dissolution.

Consistent with the theory of alternative stable states in shallow lakes (Scheffer 1989), there is a delicate balance that governs whether the area on the western edge of the sand zone is SAV-dominated or characterized by abundant phytoplankton. One process that can lead to a decline in SAV coverage is physical scouring associated with tropical storms and hurricanes (Jin et al. 2011). The other important factor that reduces SAV dominance is light limitation, which is largely controlled by water depth, in conjunction with the amount of dissolved color and concentrations of total suspended solids (living, dead, and inorganic) in the water column. When SAV cover declines, the plants no longer take up nutrients from the water column, and nutrients that were previously bound in the macrophytes are liberated and become available to phytoplankton (often cyanobacteria), which grow prolifically under the nutrient-rich conditions (Phlips et al. 1993b, 1995). The cyanobacteria bloom of summer 2018 began in the southwest near-shore zone, and occurred after SAV biomass had declined, following a period of high lake level (Havens pers. comm.).

Application of “alternative stable states” theory in Lake Okeechobee is appropriate for understanding the switching of the dominant primary producer community that inhabits the area between the sand zone and western marsh. Prolonged periods of deep, turbid water, or events such as tropical storms and hurricanes, which uproot higher plants and re-suspend substantial amounts of sediment, lead to the demise of SAV and promote cyanobacterial blooms because of P release to the water column that occurs upon the loss of the SAV (Havens et al. 2011). Such algal blooms, in turn, further attenuate light penetration, preventing recovery of macrophyte stands, even if bottom substrate conditions are ideal for SAV growth. Re-establishment of the macrophyte community often does not happen even if the system returns to the point, with respect to nutrients and light, at which the switch from SAV to phytoplankton occurred. Scheffer (1989) discussed the resistance of algal-dominated (turbid) lakes to return to a former, macrophyte-dominated, clear-water state. In Lake Okeechobee, it may take “extraordinary” conditions, such as a dramatic drop in lake level (Jin et al. 2013), with associated changes in dissolved color and nutrient concentrations, to enable SAV re-colonization of the western sand zone. Schelske et al. (2010) proposed that anthropogenic darkening of Lake Apopka led to reduction of photosynthetically active radiation (PAR) reaching the lake bottom, which triggered the lake-wide shift from macrophytes to algae in the late 1940s. Continued algal blooms in Lake Apopka, together with a shift in the lake from consolidated peat sediments to an algal-derived, watery bottom deposit, have prevented the re-establishment of widespread macrophyte beds.

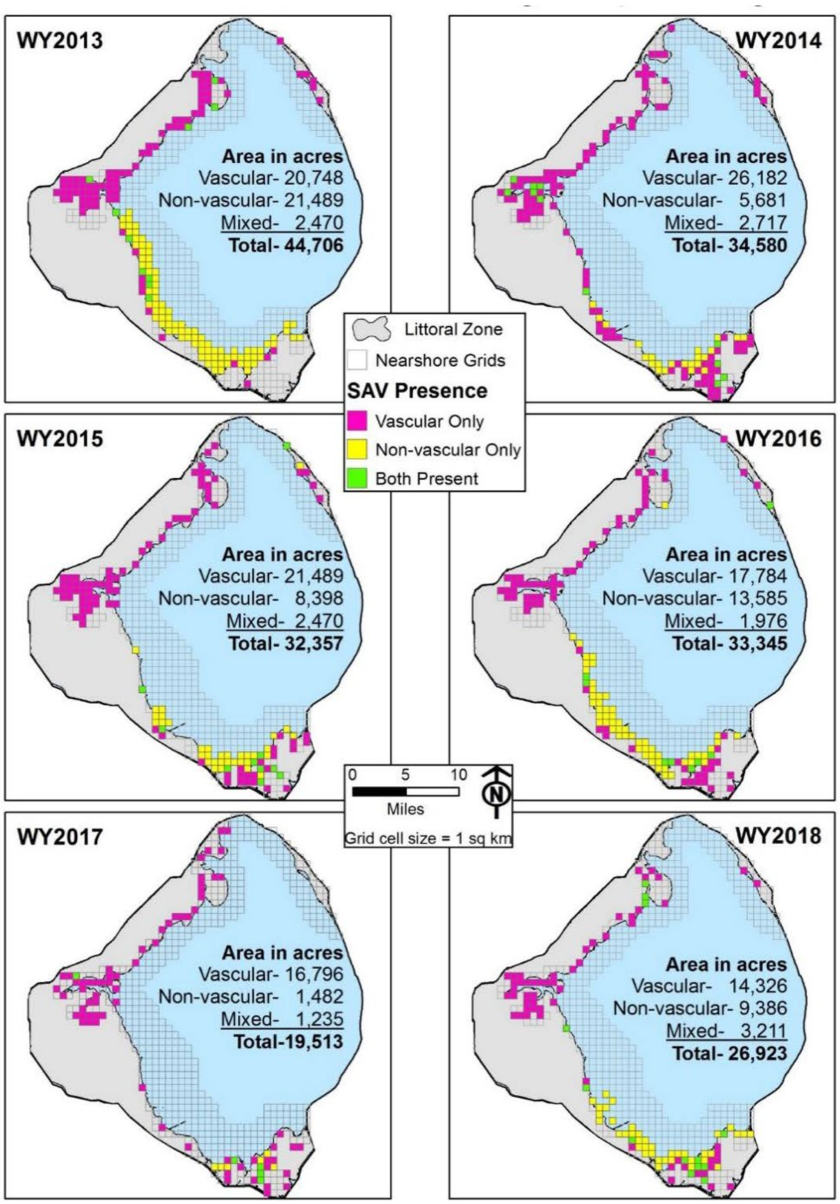


Figure II-7. Maps of annual nearshore SAV for water years (WY) 2013-2018. Vascular species included *Hydrilla verticillata*, *Utricularia* spp., *Ceratophyllum* spp., *Vallisneria americana*, *Potamogeton* spp., and *Najas guadalupensis*. Macroalgae *Chara* spp. and *Nitella* spp. were the only non-vascular species. “Mixed” indicates presence of both vascular and non-vascular species in the same grid cell. Sampling was carried out in August of each year. From Welch et al. (2018) Draft 2019 South Florida Environmental Report – Volume I, Chapter 8B: Lake Okeechobee Watershed Annual Report.

SAV in Lake Okeechobee prevents wind-generated turbulence from reaching the lake bottom, thereby stabilizing otherwise erodible sediments and maintaining clear-water conditions. SAV and their epiphytes also compete with algae and cyanobacteria for nutrients, reducing the likelihood of large phytoplankton blooms, even at relatively high nutrient concentrations (Hwang et al. 1999, Havens et al. 2001), and they contribute to long-term sequestration of nutrients in sediments. The near-shore, SAV-dominated zone provides other ecosystem services, such as creating habitat for maturing fish when they transition from the littoral to the pelagic zone (Fry et al. 1999). As juveniles, such fish are an important component of the diet of many wading birds that nest in the littoral zone.

Given the important role of SAV in the lake with respect to suppression of sediment re-suspension, nutrient uptake, and habitat for invertebrates, fish and other vertebrates, decisions regarding stage regulation should consider factors that affect macrophytes. Light requirements of taxa such as *Vallisneria* (Grimshaw et al. 2002) and exotic *Hydrilla* (Bowes et al. 1977; Van et al. 1976) are known. There is also information about SAV recovery following high-water periods (Steinman et al. 2002; Havens et al. 2004). Harwell and Havens (2003) documented that the seed bank in near-shore sediments makes the SAV community resilient after periods of plant loss.

The SFWMD (NRC 2018) evaluated how SAV cover was related to minimum lake stage during the growing season from May to August, for the years 1999-2016. Spatial extent of macro-algae was inversely related to the May-August minimum lake level. That is, macroalgal cover was greatest at lowest May-August stage, and spatial extent declined at higher lake stages. Coverage of vascular plants was inversely related to minimum lake level two years prior, reflecting a lag in growth response of the higher plants. Minimum lake level explained >84% of the variability in annual submerged plant cover in the lake (Figure II-8).

Spatial coverage of macroalgae and higher plants displays a strong inverse relationship with minimum lake level during the growing season, between May and August (NRC 2018). For years in which the lake level fell to 12 ft (~3.7 m), total SAV cover was three times greater than in years when the lake level declined to only 15 ft (~4.6 m). Maintenance of widespread SAV in Lake Okeechobee requires very low lake level during the growing season.

Havens and colleagues (2002) were able to accurately predict (R^2=0.75) the spatial extent of *Chara* using a model with water depth and sediment type as independent variables. The relation between total SAV spatial extent (microalgae and vascular plant species) and minimum annual lake level was also highly significant, but lake level explained only 45% of the year-to-year variation in coverage of vascular plants alone, i.e., the taxa most important for fish habitat. It is not clear what additional factors are important in controlling vascular plant extent. Plant responses to ambient conditions may be linked to antecedent conditions, with respect to wind-generated turbulence, turbidity, nutrient concentrations, and algal blooms, as well as presence of a seed bank. A single year of high-stage conditions may have relatively little impact on a healthy, widely distributed SAV community. On the other hand, a high-water year may have serious consequences for SAV populations that survived several consecutive years without a low-stage period in which to recuperate.

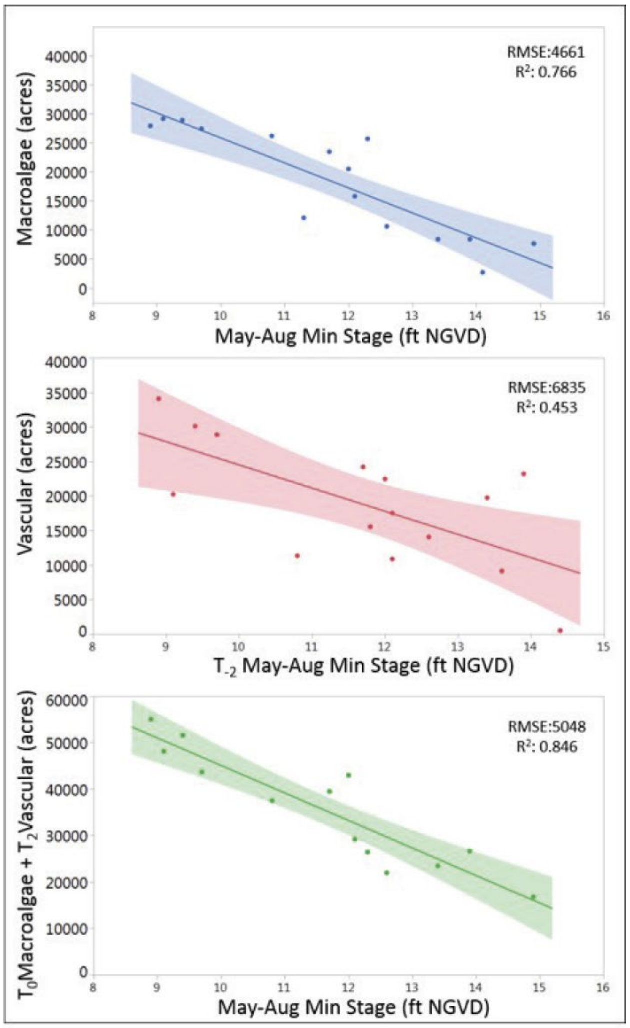


Figure II-8. Regression models of lake stage and submerged plant cover developed using yearly maps of vegetation in Lake Okeechobee, for the period 1999-2016. Shaded bands represent the 95% confidence interval on the regression. From NRC (2018). DATA SOURCE: Zach Welch, SFWMD, 2018.

Although progress has been made in establishing short-term relationships between lake stage, light penetration in the water column, and the spatial extent of SAV in Lake Okeechobee, more needs to be determined regarding longer-term relationships between lake level, light attenuation and plant distributions. Havens developed a successful, simple model that used TSS and water depth from the previous year as independent variables to predict the spatial extent of SAV in the lake and the location of SAV in a 1-km^2 grid in the near-shore zone. Attempts to predict SAV extent two years and three years later, however, showed a precipitous decline in model capability.

All aspects of lake stage (seasonality, rate of change, duration) and related sediment re-suspension, influence plants and animals in the near-shore, sand-bottom and littoral zones of the lake (Havens and Gawlik 2005; Johnson et al. 2007). Planning and execution of future water releases should consider these impacts, and the fact that the hydrology of the system may undergo changes in response to inter-annual and decadal climate variability (James et al. 2008; Jin et al. 2011; Havens and Steinman 2015).

Submerged aquatic vegetation and emergent bulrush (*Scirpus* [*Schoenoplectus*] spp.) are excellent indicator taxa for understanding the relation between lake stage and biota in Okeechobee. Bulrush occurs in bands at bottom elevations of 10-10.5 ft (3.0-3.2 m) above mean sea level (AMSL), along the western area of the lake, about 100 feet (~30 m) from the edge of the littoral zone. Bulrush can be considered a keystone species in Lake Okeechobee, in that its presence affects numerous other taxa (Aumen and Wetzel 1995). Much as mangroves protect coastal environments by attenuating wind energy and preventing sediment erosion, bulrush stems dampen wave energy in the near-shore zone of Lake Okeechobee, enabling SAV to survive there. And bulrush also protects the eastern edge of the littoral zone from wind-generated wave erosion. Bulrush stands serve as habitat for juvenile fish, and stem clusters are inhabited by macro-invertebrates and are covered with periphyton, the latter being important primary producers in the lake food web.

Bulrush persists at inundation levels ≤ 3 ft, but at water depths > 3 ft, especially for prolonged periods, stands can fail (Smith and Smart 2005; Harwell and Sharfstein 2009). Thus, prolonged periods of lake level > 15 ft AMSL could have negative impacts on emergent plant populations. There is a need, however, to conduct more pond experiments and accumulate additional *in situ* data to evaluate the response of *Scirpus* populations over longer periods of inundation. It is not necessarily water level *per se* that negatively impacts emergent plant growth and survival, but rather, associated factors such as strong wave energy, currents, and high turbidity. Furthermore, sufficient water must remain in the marsh zone to sustain the diverse plant community that inhabits the region, as well as the invertebrate and fish populations that sustain wading birds.

There remain substantial knowledge gaps regarding the relation between bulrush health and lake stage (magnitude, duration, rate of change). Furthermore, negative impacts on bulrush stands can have repercussions at other trophic levels. For instance, one consequence of bulrush uprooting under high lake stage is that plants accumulate along the littoral fringe, creating a barrier to fish movement between the marsh and open lake (Havens and Gawlick 2005). More needs to be done to ascertain under what circumstances, and how quickly, bulrush stands recover following a sustained period of deep water. Tubers on the lake bottom may be responsible for much of the regeneration that occurs subsequent to plant loss. Following a drought, bulrush appeared to recover in two years, even after having been knocked back by three consecutive years of high water. It is, however, unknown what might have happened had the drought not occurred. It may be possible, going forward, to monitor the spatial distribution of emergent macrophytes remotely and better link plant cover to lake hydrology. Once such relations are well understood, and ecological targets are established, it should help water-level regulators make better-informed decisions. Again, such choices may be highly constrained by factors beyond the control of “decision-makers.”

Fish and Lake Stage

Havens et al. (2005) evaluated the response of largemouth bass (*Micropterus salmoides*), SAV and emergent plant coverage to variations in water level in Lake Okeechobee over a five-year period. Lake stage had been high during the five years leading up to the study (1995–1999), and consequently SAV displayed low biomass and spatial coverage compared to values in the early 1990s. Spatial extent of emergent vegetation was also low. Electrofishing surveys found low bass densities in the SAV zone and recruitment of young fish into the population was poor. This was attributed to the lack of macrophytes. Deliberate stage reduction in spring 2000, followed by a protracted drought, lowered the water level in the lake by 3.3 feet (1 m), which evidently triggered growth of *Chara* along shoreline areas and increased water clarity. Vascular SAV germinated, but *Chara* remained the overwhelming dominant, and bass recruitment did not improve. In 2001, water level fell further and emergent plants germinated on exposed areas of the lake bottom. SAV was restricted to sites farther from shore, and *Chara* continued to dominate. Still, bass failed to respond positively. In 2002, water levels rose to moderate depth, flooding the shoreline habitat to 1.6 feet (0.5 m). Vascular SAV increased in biomass and spatial extent, and the community became structurally more complex. Emergent aquatic plants established dense stands along the western shoreline. Largemouth bass then showed strong recruitment of young fish and successful recruitment continued into 2003. The relatively short-term study, covering the period 1999-2003, suggested a positive relationship between recruitment of largemouth bass and structural complexity of the near-shore vegetation. Given the negative relationship between lake stage and SAV distribution and abundance, it is plausible that sportfish numbers could be managed to some extent using the regulation schedule. Nevertheless, further studies must be undertaken to confirm the relation between lake level and fish populations (numbers, biomass, recruitment), if such relations are to be considered in the regulation schedule planning or real-time operations in Lake Okeechobee.

Johnson et al. (2007) reviewed the existing literature on Lake Okeechobee stage, plant communities and associated biota. They found that prolonged flooding at levels exceeding 16.7 ft (5.1 m) AMSL would result in loss of SAV and wetland plants, and in turn have a negative impact on fish and other fauna. On the other hand, maintenance of water levels between 12.1 and 15.1 ft (3.7 and 4.6 m) AMSL, with periodic declines to the lowest end of the range, would be expected to result in diverse, healthy stands of SAV and emergent plant populations, and widespread habitat and enhanced food resources for bass and other fish, reptiles (alligators), wading birds and snail kites. Negative consequences of protracted low water levels might include expansion of invasive torpedo grass, which would require special control efforts, loss of aquatic (marsh) habitat for juvenile fish, and increased fire frequency in dry marshlands.

Rogers and Allen (2008) evaluated the impact of four large hurricanes (2004-2005) on Lake Okeechobee fish and found lower diversity, numbers of individuals and biomass associated with the resulting high lake stage. Whereas extreme weather events prior to construction of the Herbert Hoover Dike would also have raised the lake level, fish and other aquatic animals would have been able to migrate westward with the rising waters, into the then much larger, unconstrained marsh. Loss of habitat (SAV) and reduced area for refuge under current conditions makes protracted high water detrimental to fish, many of which are important for the local sport fishery (e.g., bass, crappie, and other centrarchids). The authors point out that hydrological constraints, i.e., inability to discharge water rapidly, make it difficult for managers to return the lake quickly to pre-storm conditions. Hurricanes reduced plant biomass, and led to reductions in total fish biomass, species richness, and community diversity. The study provided insights into the response of the fish community to extreme weather conditions, but more needs to be done to monitor fish community attributes on a regular basis, not only in response to extraordinary events and “bad” conditions.

Birds and Lake Stage

Water level in Lake Okeechobee, and its fluctuation throughout the year, profoundly affects numerous species of wading birds (herons, ibises, wood storks, roseate spoonbills, egrets) (Smith et al. 1995; Chastant et al. 2017) and endangered Everglades snail kites (*Rostrhamus sociabilis*). For the latter species, the Okeechobee marsh zone serves as the central nesting ground in a regional network of wetland systems where birds reproduce (Bennets and Kitchens 1997; Fletcher et al. 2017; Riechert et al. 2016). Kite reproductive success is related to lake stage in two ways. First, water level governs the structure of vegetation in the marsh, which in turn is related to site suitability for nesting. Rapid rises in water level that occur after birds have established nests can drown eggs or young birds. Second, historically the kite fed exclusively on native apple snails (*Pomacea paludosa*) that lay their eggs on the stems of emergent vegetation in the littoral zone. Apple snail eggs must develop above the water surface, then hatch, with young entering the water as miniature adults. Water transgressions that inundate snail egg masses drown the developing gastropods, resulting in low production (i.e., food for birds) in the coming year.

It remains to be seen how the recent proliferation of invasive South American apple snails (*Pomacea maculata*) will affect kite populations in the future. There was initial concern that the larger and thicker-shelled invasive gastropods would outcompete native snails (Rawlings et al. 2007), and negatively impact juvenile snail kites (Cattau 2010) if they could not extract the snails from their robust shells. It now appears, however, that there has been rapid evolution of the beak in some kite populations, enabling the birds to handle the exotic prey, despite their thick shells (Cattau et al. 2018). Indeed, the rapid spread of *P. maculata*, with its large mean clutch size (>2000 eggs), high hatch rate (80%; Barnes et al. 2008), and potential longevity of > 2 years (Arnold et al. 2014), may have a long-term positive impact on the snail kite population (Cattau et al. 2016). The emergence of the invasive snails as an alternative prey item makes it all the more important to understand how water level in the lake, particularly in the marsh, influences these snail populations.

Wading birds are also affected by water depths and fluctuations during the nesting season in late winter and early spring, and by vegetation structure, particularly the presence of willow (*Salix* spp.). The most advantageous conditions for wading bird reproductive success appear to include moderately high winter lake stage (15 ft (4.6 m) AMSL), followed by slow, protracted recession beginning at the onset of the nesting season, in December-January (Smith and Collopy 1995). Once nesting has been initiated, it is important that there be no abrupt stage reversals (transgressions), which could drown established bird nests. Chastant et al. (2017) recommended that spring water levels should fall to the 13-12-ft (4.0-3.7-m) AMSL range. Low lake stage concentrates fish and invertebrates in the marsh zone, thereby providing ample prey for adult birds and their offspring. Slightly different stage recommendations apply to long-legged versus short-legged wading birds (Figure II-9).

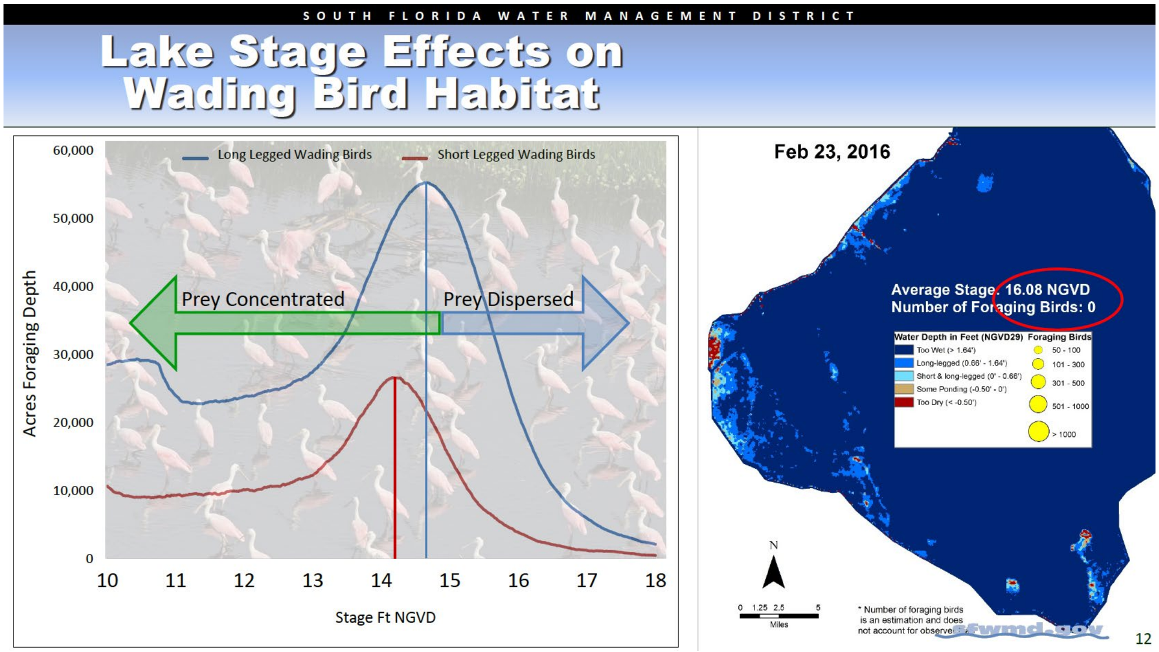


Figure II-9. Slide 12 of the USACE webinar on *How Lake Okeechobee Water Levels Affect Lake Ecology*, illustrating the effects of lake stage on long-legged and short-legged wading birds, with respect to area for foraging. Prepared by Z. Welch, Applied Sciences Bureau, SFWMD. Webinar last accessed on 30 September 2019 at: https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll11/id/3906

Lake Okeechobee Ecological Knowledge Gaps and Recommendations

Lake level, water quality and cyanobacteria blooms

One of the major threats to the ecology of Lake Okeechobee and its connected estuaries is blooms of toxic cyanobacteria, and one of the most prolific toxin producers is *Microcystis aeruginosa* (Phlips et al. 2012). Methods for determining microcystin concentrations in the lake and estuaries should be standardized to determine the role of lake blooms in controlling estuary toxin concentrations. After entering the estuaries, the distribution of toxins can be impacted by exposure of blooms to saline conditions (Black et al. 2011). Measures of both extra-cellular and intra-cellular microcystin concentrations in the lake and estuaries are needed to address the ecological and human health consequences of high toxin values. In the lower estuaries, cell lysis can greatly elevate toxin levels in the aqueous phase.

Efforts have been made to link hydrological conditions in Lake Okeechobee and the incidence and severity of cyanobacteria blooms, but most such connections are largely qualitative (USACE 2007). Furthermore, field data on water quality variables are often collected in response to

Microcystis outbreaks, i.e., after the fact, thus making it difficult to discern conditions that gave rise to a bloom. Two approaches can be used to better understand the factors that lead to harmful algae blooms, and link those factors, in turn, to lake hydrology. First, analysis of historical limnological data on nutrient concentrations, dissolved color, TSS, light penetration and algal densities, in conjunction with lake level information, may enable identification of antecedent water-column conditions that are conducive to cyanobacteria bloom formation. Second, going forward, sampling strategies should be developed to monitor limnological variables at sufficiently high spatial and temporal resolution to establish the causal connection between limnological conditions and cyanobacteria blooms.

As triggers of cyanobacteria are better understood, remote sensing and *in situ* observations of key lake variables should be integrated with predictive models to forecast the onset and demise of *Microcystis* blooms in both Lake Okeechobee and the northern estuaries in real time. These models could be used to help select lake water-release locations to avoid introducing substantial cyanobacteria biomass to the estuaries, if it is determined that *Microcystis* blooms in the estuaries originate in the lake and are delivered in discharged water.

It has been more than a decade since the last comprehensive study of sediment distribution and characteristics in Lake Okeechobee (Yan and James 2012), despite the acknowledged importance of sediments in limiting light penetration and supplying phosphorus to the overlying water column (internal loading), through diffusion of dissolved nutrient forms from the lakebed and possible desorption of available P during sediment re-suspension events. If recent sediments have become increasingly saturated with adsorbed P, they may have lost their capacity to sequester additional nutrient. External P loading also deserves further scrutiny. Whereas Fisher et al. (2005) demonstrated the importance of internal P loading to the nutrient budget of the water column, external loads remain high, both because of legacy nutrients in the drainage basins north of the lake and because of ongoing land uses such as dairy cattle ranching and improved pasture development.

It is likely that high anthropogenic P loading is largely responsible for the lake being nitrogen-limited today (Havens 1995), and such N-limitation influences the composition of the phytoplankton community. One question is “why, if the system is nitrogen-limited, is the non-fixer *Microcystis* so important?” Whereas N-fixing taxa are assumed to have a competitive advantage under N-limiting conditions, nitrogen fixation is energetically costly, perhaps accounting for the dense blooms of *Microcystis*.

Submerged aquatic macrophytes

The SAV community east of the marsh zone in Lake Okeechobee serves as a bellwether of aquatic ecosystem health and is important for overall lake ecology by virtue of its ability to utilize water-column nutrients, attenuate wave energy, stabilize sediments and provide habitat for invertebrates and fish species. Abundance and spatial distribution of SAV are related to water-column variables, including nutrient concentrations, water depth, dissolved color, and total suspended solids (organic and inorganic), all of which affect light extinction (Jin and Ji 2013). These variables, in turn, are related to factors such as lake hydrology and wind speed (sediment resuspension). Historical data on lake stage and the limnological variables that influence light penetration in the water column, along with information on the abundance and distribution of submerged plant taxa, will enable a better understanding of how the magnitude and duration of high stage affects the SAV community.

It is also critical to know what conditions best promote recovery of submerged macrophytes, and which taxa are most resilient following a protracted period of reduced plant coverage. Related to rejuvenation of plant populations, it would be helpful to know more about the life histories of each taxon, with respect to how each species regenerates (e.g., vegetatively from remaining stock, from seeds, turions), and how quickly each builds new biomass. Apparently, *Chara* recovers rapidly when lake level declines, whereas there may be a substantial delay, 1-2 years, in recovery of *Vallisneria*, *Potamogeton* and *Hydrilla*, following a protracted high stage. SAV censusing and measurement of associated limnological variables should be conducted in the future, at high spatial and temporal resolution, to better identify the antecedent conditions (magnitude and duration of high stage) that lead to submerged plant loss. Additionally, studies on the re-establishment of SAV in suitable habitats need to be carried out, focusing on sources of propagules (seeds or drifting plants). This will enhance understanding of the lag between re-establishment of lake stage conducive to vascular SAV recovery, and subsequent proliferation of macrophytes. Linking the proximal causes of plant demise to lake stage may enable better incorporation of SAV health status into decisions about water releases.

Hydrologic management for overall SAV health in Lake Okeechobee is not straightforward. Under long periods of high stage, there is more wave damage, the marsh area is reduced, and uprooted vegetation can create a barrier to fish movement between the marsh and open lake. High lake level also leads to introduction of nutrients into the marsh interior, promoting cattail (*Typha*) growth and loss of some woody species. On the other hand, protracted low stage enables invasion by upland species like torpedo grass, and emergent marsh vegetation advances into the zone typically occupied by SAV, thereby necessitating management protocols such as controlled burns.

Emergent plants

Scirpus (bulrush) has been identified as an emergent plant of key importance in Lake Okeechobee for its role in supporting epiphytic lifeforms that serve as the base of the aquatic food web, for diminishing the impact of wave energy in the nearshore littoral zone, and for providing fish habitat. There is some information about its survival under different lake stage conditions, from both empirical studies of plant distributions in the lake and controlled pond experiments (Smith and Smart 2005). In general, prolonged high stage that inundate stems to a depth >3 feet have a deleterious impact on plants. Spatial extent of bulrush was inversely related to lake level in the previous year, with lake stage explaining 96% percent of inter-annual variability in plant cover.

Longer-term study is required to fully understand what conditions are detrimental for bulrush, i.e., elevated stage *per se*, or associated factors, including high-energy conditions, turbidity, etc. Furthermore, whereas the magnitude of a lake high stage may be significant, other aspects of lake transgressions may be important also, including the rate of water-level rise, the duration of the high stage, and the prior health condition of plants subjected to high water.

Whereas protracted deep-water conditions have been shown to negatively impact bulrush stands, less is known about the recovery process for *Scirpus*, following lake recession. In the SFWMD study, three consecutive years of high water were followed by two years of drought, during which bulrush demonstrated substantial recovery. But more study is required on the amount and rate of bulrush recovery, following a high-water event. Completed studies prompt further questions, such as: 1) how will bulrush stands fare under longer, i.e., more protracted high-water periods? 2) how low, for how long, and when in the seasonal cycle must the water level in the lake decline to achieve satisfactory bulrush recovery? Lastly, it will be necessary to establish a desired target for *Scirpus* abundance and distribution, which may enable development of adaptive management strategies through collaborations between water-level regulators and ecologists.

A number of other native and exotic plant species characterize the marsh community in Lake Okeechobee (e.g., *Nuphar advena*, *Nelumbo lutea*, *Polygonum densiflorum*, *Pontederia cordata*, *Sagittaria lancifolia*, *Sagittaria latifolia*, *Thalia geniculata*, *Typha* spp., *Cladium jamaicense*, *Juncus effusus* subsp. *solutu*s, *Phragmites australis*, *Cicutus mexicana*, *Sambucus nigra* subsp. *canadensis*, *Cephalanthus occidentalis*, *Salix caroliniana*, *Myrica cerifera*, *Annona glabra*, *Urochloa mutica*, *Panicum repens*, *Ludwigia peruviana*, *Schinus terebinthifolia*) (Richardson and Harris 1995). Some have received considerable attention because, for example, they serve as nesting sites for wading birds, e.g., willow (*Salix*), which declines under high-water conditions (David 1994a, b). All submerged, emergent and floating-leaved taxa contribute to the complex structure on the west side of the basin that serves as habitat for aquatic invertebrate, fish, amphibian, reptile, and bird species. Some plant taxa, both native and exotic, are of concern, and apparently respond positively to nutrient inputs to the marsh, which occur under high-stage conditions (e.g., *Typha* sp.). The marsh zone, which represents about 18% of the enclosed lake basin, should be a priority target for linking hydrology and ecology, given its importance as habitat for diverse fauna, including numerous species of wading birds and taxa of special concern, such as snail kites.

Fish

Despite the economic importance of the sport fishery in Lake Okeechobee (Miller et al. 1990) and the vital role of fish as prey for wading birds, there is a relative paucity of information about fish populations in Lake Okeechobee. Some studies have revealed the connection between fish distribution patterns and habitat variables including substrate composition, turbidity, site depth, lake stage (Bull et al. 1995; Johnson et al. 2007; Rogers and Allen 2008), and the trophic level occupied by taxa in the lake (Fry et al. 1999). Despite the relatively depauperate fish fauna in peninsular Florida, at least 43 species of fish were captured in Lake Okeechobee, of which 36 were freshwater taxa (Ager 1971).

Given the correlation between lake stage and SAV cover, and the importance of SAV as habitat for many fish species, it is critical to link the Lake Okeechobee regulation schedule to aspects of fish population status (condition, recruitment, demographics) quantitatively, for both sport and non-sport species. This will require sampling not only in response to "crises," but on a regular basis, to evaluate the factors that maintain healthy fish populations. As for submerged plants, some fish taxa may be more resistant or resilient than others to less than optimal environmental conditions, with factors such as habitat suitability, mobility, time to sexual maturity, and food availability influencing recovery of populations following a decline.

Birds

Lake Okeechobee and surrounding wetlands are important habitats for many species of migratory and resident birds, some of which are of special concern (e.g., snail kites and bald eagles). Breeding success of bird populations is intimately tied to water level in the western marsh, in that sufficient water is required to provide habitat for invertebrate and fish prey species, and to maintain emergent vegetation (e.g., *Salix*) for bird nesting sites. Excessive water, or sudden, pronounced reversals of lake-level decline in the breeding season, negatively impact bird populations by drowning nests, or in the case of snail kites, drowning gastropod egg masses, which are laid on stems above the water line. Likewise, a rapid lake-level drop from March through July can have negative consequences for breeding birds.

Much research on lake hydrology and birds has focused on the snail kite, which is listed by both the state of Florida and the federal government as an endangered species. Okeechobee snail kites are important for establishing connectivity between populations north and south of the lake. Whereas the direct impacts of water level on bird nesting success have been explored, less is known about indirect effects, such as how the proliferation of harmful algal blooms (linked to hydrology) affects water bird and raptor foraging, or how such blooms might be connected to avian vacuolar myelinopathy (AVM), caused by a neurotoxin of unknown origin.

Going forward, it will be important to track how different bird species populations respond to water level regulations throughout the annual cycle. A number of questions could be addressed: 1) Are optimal conditions for snail kites advantageous for most other species of birds in the marsh? 2) Do birds re-locate to alternative nesting sites in years when sub-optimal conditions are present at the beginning of the nesting season? 3) How quickly do bird populations rebound following one or several poor breeding seasons? The answers to such questions could be incorporated into release guidance flowcharts regarding water releases.

Lastly, efforts should be directed at evaluating the social and economic value of improving environmental conditions in Lake Okeechobee and receiving waters. Development and implementation of LOSOM is complex and requires substantial financial and intellectual investment. If the social and economic benefits of improved regulation under LOSOM can be expressed in economic terms, this will facilitate communication of the rationale for LOSOM to the public.

Lake Okeechobee Ecological Performance Measures

Lake Okeechobee performance measures used to develop LORS2008 include:

- Extreme low stage: Frequency and duration below 11 ft NGVD
- Extreme high stage: Frequency and duration above 17 ft NGVD
- Percent of time within 12.5-15.5 ft stage envelope
- Number of times stage >15 ft for more than 365 days
- Number of exceedances of Lake Okeechobee Minimum Water Level and Duration exceeded (should not be below 11 ft for more than 80 days)

These performance measures were largely developed based on the body of research regarding the influence of lake levels on lake water quality, SAV, emergent plants, fish, and birds detailed above. Over the long term, however, use of simplified, event-based hydrologic surrogates for lake ecological performance measures in LOSOM planning is not recommended. New hydrologic measures should be developed that better take antecedent hydrologic/ecologic conditions, the timing, duration, and frequency of events, and ecosystem resilience, into account.

Development of improved lake ecological performance measures will require improved understanding of how lake stage (magnitude, rate of change, duration, etc.) affects water quality variables and, in turn, lake biota. Establishment of target ecological metrics is subjective and involves identifying meaningful “indicators” of ecosystem integrity that are sensitive to changes in lake level and linking them to lake stage quantitatively. The SFWMD has developed hydrodynamic, water quality and ecologic modeling tools for Lake Okeechobee that should be useful for improving lake performance measures. For example, using 10 years of data, Jin and Ji (2013) developed the Lake Okeechobee Environment Model (LOEM), which relates lake stage to water quality variables and spatial distribution of SAV. They demonstrated that SAV growth is controlled primarily by light and nutrients. Light availability for SAV growth is a function of water depth and turbidity, the latter dependent on suspended sediment and algal concentrations.

Linking hydrologic processes in Lake Okeechobee to ecological conditions is challenging, in that biotic populations respond not only to instantaneous lake stage, but to rate of change and duration of high/low lake levels, as well as to the antecedent health condition of the biotic population of interest. Model calibration may be based on measurements collected over a limited time span, which fail to capture the full range, in terms of magnitude and rate of hydrologic change, that may occur under future climate scenarios. Furthermore, aspects of the lake system have changed through time, implying that relations between hydrologic and ecologic conditions in the past may not hold in the future. The distribution, thickness and geochemistry of the lake sediments all appear to have changed over decadal time spans, perhaps altering their susceptibility to wave-induced resuspension and modifying their ability to adsorb dissolved P and contribute to internal nutrient loading. In addition, components of the biota respond to hydrologic changes at different rates, for different reasons. For example, recovery of a population, following a period of sub-optimal water column conditions, may be affected by: 1) antecedent health conditions, 2) life history differences, e.g., rapid turnover rates of invertebrates relative to those of fish and birds, and 3) connectivity to populations beyond the confines of the dike, such as mobile bird populations.

In spite of these challenges, the LOEM model is a promising tool that could be used in concert with the South Florida Water Management Model to link water quality and ecological outcomes to hydrology and water management decisions in a more rigorous quantitative manner. Accelerated investment in this and other modeling tools is recommended so that they become an integral part of the planning and operations decision-making toolbox. Linked hydrologic-water quality-ecologic modeling systems could be used both in the LOSOM planning process to screen alternative operating plans, and in monthly operational positional analyses to probabilistically forecast lake and estuarine ecologic conditions, based on antecedent ecological conditions and forecast climate and hydrologic conditions.

Recommendations

- Design sampling protocols (water column physical/chemical variables, algae and cyanobacteria, SAV, emergent plants, fish, birds) that have sufficiently high spatial and temporal resolution to better connect hydrologic and ecologic conditions in the lake. Identify the conditions that precede in-lake cyanobacteria blooms, so that the locations and timing of water releases can be selected to avoid bloom events.
- Assess the current spatial distribution and stratigraphic characteristics (grain size, density, nutrient forms) of sediment in the mud zone of the lake, to better model sediment resuspension, determine if resuspended surface muds are a P source or sink to the water column, and re-evaluate the relative contributions of allochthonous and autochthonous phosphorus loading to the lake.
- Standardize the way samples for mycrocystin analysis are collected, processed and measured, determine if all *Microcystis* strains produce toxin, and identify the causes of microcystin release.
- Determine whether cyanobacteria in the St. Lucie and Caloosahatchee Estuaries are regularly "seeded" by existing blooms in the lake or are simply a consequence of high nutrient discharge and sufficient water residence time in the receiving waters.
- Couple remote sensing and *in situ* observations with predictive models to forecast the onset and demise of *Microcystis* blooms for real-time operations. These models could be used to help select lake water-release locations to avoid introducing substantial cyanobacteria biomass to the estuaries.
- Enhance the simplified, event-based hydrologic surrogates for lake ecological performance measures used in LORS2008 planning. Better hydrologic measures should be developed that account for antecedent hydrologic/ecologic conditions, the timing, duration, frequency of events, and resilience of ecosystem components. All hydrologic performance measures should be compared systematically to observed/historic ecosystem performance to ensure their validity. Their utility should also be verified by analysis of the social and economic "costs" associated with failure to achieve specific performance measures.

- Accelerate investment in the Lake Okeechobee Environment Model (LOEM) so that it can become an integral part of the planning and operations decision-making toolbox. LOEM could be linked with the South Florida Water Management Model and in the LOSOM planning process to screen alternative operating plans. It could also be used to broaden monthly operational positional analyses that currently forecast climate and hydrologic conditions to also incorporate forecasts of lake ecologic conditions.

III. Lake Okeechobee Influences on the Estuaries of the Greater Everglades

Introduction

Water released from Lake Okeechobee adds to the surface water and groundwater flows that supply water for human and ecological needs before they make their way to the ocean that surrounds the Florida Peninsula. The semi-enclosed coastal embayments where this freshwater mixes with ocean water are the productive coastal estuaries of south Florida (Figure III-1). Before the engineering of the Everglades-Lake Okeechobee watershed, water that overflowed from Lake Okeechobee fed the wide sloughs in the Everglades and moved south in the Shark River and Taylor Sloughs to eventually discharge into the Ten Thousand Islands/Shark River Estuary, Florida Bay and Biscayne Bay.

Figure III-1. Map of the northern estuaries (St. Lucie and Caloosahatchee River Estuaries) and southern estuaries (Biscayne Bay, Florida Bay, and Ten Thousand Islands/Shark River Estuary). Source: South Florida Ecosystem Restoration Program Overview (USACE 2016).

The current system of dikes, canals, pumps, water conservation areas and nutrient removal areas has redistributed much of the water that leaves Lake Okeechobee into the northern estuaries. The northern estuaries, the Caloosahatchee River Estuary (CRE) to the west and the St. Lucie Estuary (SLE) to the east, historically had relatively small watersheds that were largely independent from the Lake (Figure III-1). The quantity, quality, timing and distribution of the freshwater runoff into the northern and southern estuaries all impact their ecological condition. With the exceptions of the Ten Thousand Islands/Shark River Estuary, the historical state of the estuaries of the Greater Everglades was that of generally clear water overlying well-developed and productive benthic ecosystems supported by submerged aquatic vegetation (SAV) in sandy-muddy areas and oyster reefs (in the northern estuaries) and coral-sponge communities (Florida and Biscayne Bays) on hard bottom habitat.

Estuaries are transitional ecosystems between land and ocean. Freshwater runoff interacts with rainfall and evaporation over the estuaries and tidal exchange with the coastal ocean to influence the salinity and spatio-temporal gradients in salinity within estuaries. Salinity has a direct influence on the plants and animals that form the productive ecological communities of estuaries. Salinity is a major environmental factor that affects aquatic organisms in estuarine ecological communities, such that these species can be described according to their salinity tolerances. Stenohaline organisms have restricted salinity tolerances, in contrast to euryhaline organisms with broad salinity tolerances. Different stenohaline organisms thrive only in freshwater, seawater, or in mixtures of both, whereas euryhaline organisms thrive in many different salinities. For example, most freshwater species cannot tolerate a salty environment because of osmoregulatory stress. Thus, any change to ambient salinity has the potential to disrupt vital biological processes that sustain plants and animals. Ambient salinity is a major influence on reproduction, larval dispersal and recruitment, geographical distribution, and behavior of marine species (e.g., Koch et al. 2007; McMillan and Moseley 1967; Sellers and Stanley 1984). Hence, salinity changes in Florida's estuaries in response to Lake Okeechobee operations will influence the structure of communities and the boundaries of species distribution.

In addition to modifying the distribution, volume and timing of freshwater runoff and the salinity of estuaries, human activities in the greater Everglades watershed also have increased the loading of many organic and inorganic contaminants and pollutants, including the nutrients nitrogen (N) and phosphorus (P), which are required by plants. Most naturally occurring forms of N and P are non-toxic, but they may still cause biological changes in receiving water bodies. At high rates of nutrient loading, planktonic algal blooms proliferate in estuaries (Duarte 1992). Toxic algal species can also be introduced into the estuaries when those species bloom in Lake Okeechobee and water from the Lake is discharged into the estuaries.

Primary producers (vascular plants, macroalgae, microalgae and cyanobacteria) only grow until an important resource reaches critically short supply. In aquatic systems, the resources that often limit primary producer biomass and species composition are light, N and P (Elser et al. 2007). In general, nutrient-poor waters have clear water and high light penetration, whereas nutrient-rich water bodies have opaque water and low light penetration. In most natural freshwater ecosystems, P is the resource that limits primary producer biomass; however, primary producers in the world's estuaries most often are limited by N (Howarth 1988). Human alteration of the nutrient loads into natural ecosystems can change the relative importance of N and P in controlling primary producer biomass. And, since water management in the Greater Everglades has changed the flow of freshwater from areas that harbor pollutants, it also has increased the delivery of toxic substances, such as pesticides and heavy metals, to the estuaries (SFWMD 2002).

Freshwater Quality Impacts on Estuary Ecology

The natural state of the southern estuaries that historically received runoff from the Lake Okeechobee-Everglades watershed is one of P limitation (Table III-1), making these estuaries part of a small group limited by P rather than N (Ten Thousand Islands: Boyer 2006; Shark River: Chen and Twilley 1999; Florida Bay: Fourqurean et al. 1993; Fourqurean et al. 1992; Biscayne Bay: Lirman et al. 2014). The recognition of the importance of P in structuring the plant communities and primary production of the Everglades marshes and the southern estuaries focused the attention of ecosystem managers on controlling the concentrations and availability of P in Everglades ecosystems to restore the southern Everglades (Sklar et al. 2005). In contrast to the ecological systems in the southern Everglades, the northern estuaries are N-limited. In the CRE, both planktonic (Heil et al. 2007) and benthic primary production (Lapointe and Bedford 2007; Milbrandt et al. 2019) are limited by N availability. Phytoplankton are N-limited in the upper reaches of the SLE (Lin et al. 2008; Yang et al. 2008), as well as toward the seaward end of the estuary (Kramer et al. 2018). Benthic algae also are N-limited in the SLE (Lapointe et al. 2017). This dichotomy – N-limitation in the northern estuaries and P-limitation in the southern estuaries – implies that different strategies are needed to protect northern and southern estuaries from environmental harm that can result from releases of nutrient-laden Lake Okeechobee water.

Molar ratios of N:P in primary producer biomass have long been used to assess the relative availability of N and P, and therefore, identify the limiting nutrient (plankton: Redfield 1958, submerged aquatic plants: Atkinson and Smith 1983). The rule of thumb based on N:P in planktonic primary producer biomass treats ratios > 16 as indicative of P limitation, N:P < 16 as indicative of N limitation and N:P ≈ 16 as an indication that light availability or some other factor is likely limiting. For more structurally complex macroalgae and non-woody vascular plants, N:P > 30 indicates P limitation, N:P < 30 indicates N limitation and N:P ≈ 30 indicates light is likely limiting (Atkinson and Smith 1983; Duarte 1990; Fourqurean and Rutten 2003). Ultimately, the nutrient that limits primary production in estuaries is a function of: the relative amounts of N and P delivered in freshwater and marine water entering the system (N:P ratio); the loss of N and P to biogeochemical processes such as denitrification, adsorption and sedimentation; and the extent to which nitrogen fixation can make up N deficits (see Howarth 1988 for review). The combination of these factors often leads to N limitation in estuaries (Howarth 1988; Ryther and Dunstan 1971). In their N-limited nature, the CRE and the SLE are similar to most subtropical and temperate estuaries. In contrast, P limitation occurs in estuaries where either N:P in loads are very high (e.g., Harrison et al. 1990), the residence time for water is long enough to allow the products of nitrogen fixation to accumulate (Smith 1984), or both.

Table III-1. Properties of estuaries receiving water from Lake Okeechobee discharge

Estuary	Area mi^2	Volume ($10^6 ft^3$)	Discharge, Q (10^3acre-ft yr^{-1})	Residence Time V/Q (yr)	N:P in loading (molar ratio)	Limiting nutrient
Caloosahatchee	25	2048	816	0.1	21-25.2[1]	N
St. Lucie	10.4	3990	65	1.4	11-19.7[2]	N
Shark River	74	13560	972	0.3	260	P
Florida Bay	772	70629	268	6.0	242	P
Biscayne Bay	429	77692	1685	1.1	274.2[3]	P

[1] Julian and Osborne 2018; values are means for 1978-2016.
[2] Lapointe et al 2012
[3] Caccia and Boyer 2007

The southern estuaries (Shark River Estuary, Ten Thousand Islands, Florida Bay, and Biscayne Bay) are P-limited primarily because freshwater runoff carries excess N relative to P that is required to build primary producer biomass, and because biogeochemical processes in the estuaries reduce concentrations of available P (Table III-1). The vast freshwater marshes and sloughs of the Everglades ecosystem that historically transported water from Lake Okeechobee to the ocean are very efficient at retaining P because of high rates of primary production, mineral cycling by microbes and adsorption of P by carbonate soils (reviewed in Noe et al. 2001). These processes result in N:P ≈ 242:1 in the freshwater loads entering Florida Bay and 260:1 in the freshwater runoff into the Shark River Estuary (Rudnick et al. 1999). Beyond the very high N:P in freshwater runoff, plant communities in Florida Bay are P-limited because of a very long residence time for water, high rates of primary production, and carbonate sediments that adsorb P (Fourqurean et al. 1993; Fourqurean et al. 1992). Similar processes result in a P-limited Biscayne Bay. The freshwater canals that flow into Biscayne Bay are fed with water released into the Everglades, the Water Conservation Areas (WCAs) and the south Dade conveyance system from

Lake Okeechobee, as well as local inputs from their watersheds. The Dissolved Inorganic Nitrogen to Total Phosphorus ratio (DIN:TP) in Biscayne Bay canal loadings is 143.5 (Caccia and Boyer 2007).

In contrast to the southern estuaries, the northern estuaries of the Greater Everglades (CRE and SLE) are historically N-limited because of lower N:P in freshwater loads and generally shorter residence times (Table III-1). For example, N:P in the freshwater loads that enter the CRE through S-79 averaged 25.2 for the years 1978-2016 (Julian and Osborne 2018). This N:P is much lower than values observed in the southern P-limited estuaries, and it is below the N:P requirements of benthic plants. However, this stoichiometry is slightly above the critical 16:1 threshold for microalgae. Importantly, the ratio of the dissolved inorganic forms of N and P (the primary forms that spur phytoplankton growth, DIN:DIP) is 4.5:1 at the mouth of the CRE, a clear indication of N-limitation (Heil et al. 2007). Furthermore, experimental addition of N to the water column of the CRE causes enhanced phytoplankton growth, whereas addition of P has no effect (Heil et al. 2007).

The N:P in loads from Lake Okeechobee to the SLE averaged 22.8 for the period 1995-2008, and during the 2009-2011 period of low freshwater discharge, the N:P in loads averaged 21.1 (Bertolotti and Balci 2012). Note that N:P during these monitoring periods was somewhat above the 16:1 microalgae threshold, suggesting light- or P-limited conditions in the plankton during these monitoring periods. However, following the passage of two hurricanes in 2004 and 2005 and very high annual rainfall and runoff, N:P in the SLE averaged 11 (Lapointe et al. 2012). During low freshwater flows, ratios of nitrogen to phosphorus can approach 16:1, but the overall concentrations often reach low levels, which can limit phytoplankton productivity (Chamberlain and Hayward 1996). In addition, similar to the CRE, nutrient limitation assays in the water column of the upper reaches of the SLE typically confirm an N-limited condition for the phytoplankton (Kramer et al. 2018).

Adding the limiting nutrient to an estuary changes the structure of the ecosystem by causing an imbalance in the flora and fauna. All plants, including phytoplankton, microalgae, macroalgae and SAV, require light, water, and mineral nutrients, such as phosphorus and nitrogen, to grow. The required supply of nutrients is a function of the plant's relative growth rate. Plants that grow quickly require high rates of nutrient supply, whereas plants that grow more slowly require a lower rate of supply. As a consequence, rapidly growing plants are found where nutrient supplies are high, and slow-growing plants where nutrient supplies are low. High nutrient supplies are not necessarily bad for slow-growing plants, but at high rates of supply, fast-growing plants can overgrow and shade out the slower growers.

In general, the size of a plant is a good indicator of its relative growth rate, with smaller plants having higher growth rates (Duarte 1995). In the estuaries of the Greater Everglades, the fastest growing plants are the single-celled algae and cyanobacteria that live either in the water, in the sediments, or attached to surfaces, such as seagrass leaves. Filamentous algae that grow on surfaces grow slightly slower than single-celled primary producers, and more complex macroalgae, like fleshy macroalgae and calcareous seaweeds, grow slower than filamentous algae. SAV grows even slower than macroalgae. Different species of SAV have different growth rates and nutrient requirements. For example, in higher-salinity regions of the estuaries, the narrow-bladed species widgeon grass (*Ruppia maritima*) and shoal weed (*Halodule wrightii*) grow faster than the spaghetti-like manatee grass (*Syringodium filiforme*), which in turn has a faster growth rate, and therefore higher nutrient requirements, than turtle grass (*Thalassia testudinum*). It is quite common in the southern estuaries that nutrient supplies are so low they constrain the growth of even the slowest growing species (Duarte 1995; Fourqurean and Rutten 2003).

When humans increase loading of the limiting nutrient into water bodies like Lake Okeechobee or the estuaries of the Greater Everglades, there are predictable consequences that have been repeated across the world over the last century. Clear-water, nutrient-limited, SAV-dominated aquatic ecosystems are gradually replaced by faster-growing competitors (beginning with macroalgae, then followed by filamentous algae, single celled periphyton and ultimately phytoplankton at the highest nutrient loading) that eventually reach such abundance that they decrease water clarity so that sufficient light no longer reaches the SAV, which dies. Sediments that are not stabilized by SAV often begin to shift, which increases turbidity and sets up a positive feedback via light attenuation that prevents the recovery of the SAV even if nutrient loading is temporarily abated (Scheffer et al. 1993).

Flow Regime Change and Canalization Impacts on Estuarine Ecology

Florida Bay, the large estuary at the southern terminus of the Greater Everglades, currently has a spatially complex salinity regime that also varies within years and in response to rainfall. Since the 1960s, when data on salinity started to become available, Florida Bay has tended to have average salinities slightly above that of seawater, but average salinities are lower than seawater in wet years (Fourqurean and Robblee 1999). Using paleontological evidence to reconstruct salinity regimes that prevailed prior to extensive engineering of water flows in the Greater Everglades, salinity across the bay was on average 3-9 practical salinity units (psu) lower than current salinity (Marshall et al. 2014). Florida Bay is now saltier and less variable, in both time and space, than before the implementation of the Central and South Florida (C&SF) Flood Control Project (Marshall et al. 2014). Less freshwater reaches Florida Bay now than historically; using evidence from fluorescent banding of corals in southwest Florida Bay, it has been estimated that freshwater runoff has decreased by 59% (Smith et al. 1989).

The change in salinity climate has driven changes in SAV communities, a process described as "marinization," in which the most stenohaline marine species, *Thalassia testudinum*, has become more widespread and dominant than the more euryhaline *Halodule wrightii* in the late 20th century (Zieman 1982). Since the 1970s, following multi-year periods of below average rainfall, much of Florida Bay has become hypersaline (Fourqurean et al. 1993; Fourqurean and Robblee 1999; Nuttle et al. 2000), and large-scale die-offs of seagrass, followed by phytoplankton blooms, have occurred (Hall et al. 2016; Robblee et al. 1991). Even the sub-basins of Florida Bay closest to freshwater discharge have seen large increases in average salinity and changes in biological communities since 1900 (Wingard et al. 2017). Preventing ecological harm to Florida Bay requires maximizing freshwater runoff from the managed Lake Okeechobee-Everglades system and continuing to deliver freshwater with low P concentrations and high N:P. The plankton blooms in Florida Bay that followed the seagrass die-off episodes were apparently fueled by internal P loading that resulted from the death and decomposition of the SAV, rather than by P loading in the runoff from the Greater Everglades Ecosystem (Fourqurean et al. 1993; Rudnick et al. 1999).

Biscayne Bay, just north and east of Florida Bay, currently has a more stable and ocean-like salinity. However, paleoecological research suggests that mean salinity has increased broadly across Biscayne Bay as a result of the C&SF Project (Ishman et al. 1998; Wingard et al. 2003; Wingard et al. 2004). In the parts of Biscayne Bay closest to natural freshwater discharge, the paleoecological evidence suggests that those sites transitioned from freshwater ca. 1900, to oligohaline until the 1960s, then to stable marine conditions. Modern salinities are higher on average, but lower in zones in the immediate vicinity of canal discharges from the C&SF Project. These salinity changes were accompanied by shifts in the ecological communities of the bay, so the quantity of freshwater received by Biscayne Bay, from freshwater releases, does have an impact. But unlike in adjacent Florida Bay, recent data suggest that water quality of freshwater deliveries is now causing undesired changes in Biscayne Bay, especially in the more urban, northerly parts (Caccia and Boyer 2007; Millette et al. 2019), where SAV communities are being lost slowly and replaced by microalgae (Gimenez 2019).

Northern Estuaries

Caloosahatchee River Estuary

Historically, the Caloosahatchee River was sinuous where it originated near Lake Flirt, ~2 miles (3.2 km) east of La Belle at Fort Thompson (SFWMD 2018). Beginning in the 1880s, the river channel was straightened, deepened, and connected to Lake Okeechobee. This resulted in a loss of 76 river bends and 8.2 miles (13.2 km) of river length (Antonini et al. 2002). Dredging alterations continued, and by 1918, three combination lock and spillway structures had been constructed at

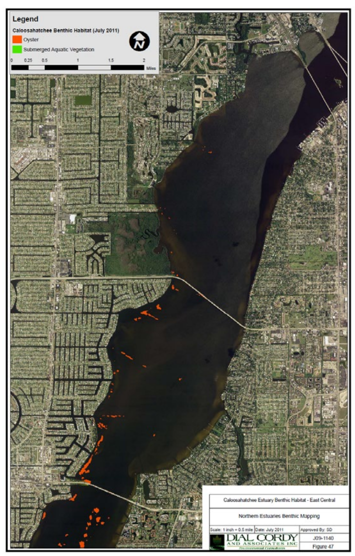
Moore Haven, Citrus Center, and Fort Thompson. By 1930, the river had been canalized and dredged to a depth of 6.5 ft (2 m) for an 80 ft (24 m) wide navigation channel. Flows within the historic Caloosahatchee River (now the C-43 canal) are controlled through the operation of multiple water control structures (S-77, S-78, and S-79). The final lock and dam structure (Franklin Lock and Dam or S-79) was completed in 1966 at Olga to assure freshwater supply and prevent upstream saltwater intrusion. Discharges from Lake Okeechobee and the Caloosahatchee River Watershed between the S-77 and S-79 structures are regulated by the United States Army Corps of Engineers (USACE). Presently, the C-43 canal spans 44 miles (70 km) from S-77 at Lake Okeechobee to S-79. The CRE begins at S-79 and spans 26 miles (42 km) to Shell Point where it empties into San Carlos Bay.

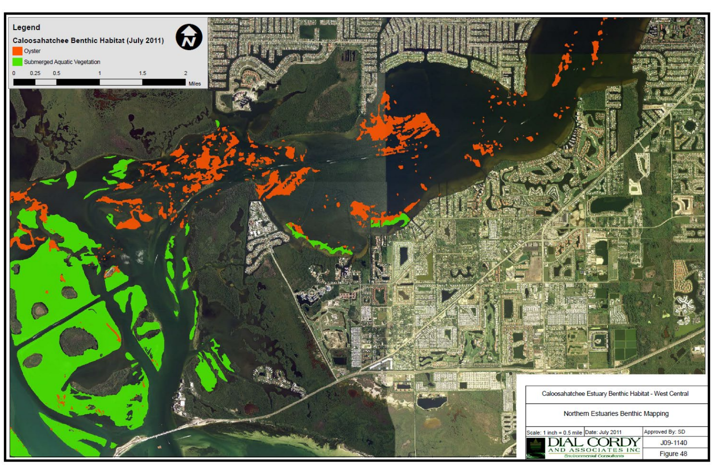
Large changes in the distribution and character of the ecological communities were concomitant with the engineering of the CRE. Although there are few historical data on these communities that predate the engineering, it is believed that the lower CRE supported large seagrass communities dominated by the seagrasses *Thalassia testudinum* and *Halodule wrightii* in waters shallower than 6 ft (1.8 m), and that the upper CRE had large beds of the freshwater/oligohaline submerged aquatic vascular plant *Vallisneria americana*. These presumed distributions suggest a relatively stable salinity regime in the CRE that varied from near fresh water at the head of the CRE and approaching seawater salinity near the mouth. Using laboratory studies of salinity tolerances for the SAV species *Halodule wrightii* and *Vallisneria americana*, pre-engineering salinity must have rarely been below 15 psu in the lower CRE and rarely greater than 10 psu in the upper CRE (Doering et al. 2002). It is also believed that oyster reefs were an important ecosystem component of the CRE (Chamberlain and Doering 1998); the Eastern oyster (*Crassostrea virginica*) was the dominant species in these communities (reviewed in Volety et al. 2009). The Eastern oyster has a broad geographical distribution and wide temperature and salinity tolerances, but adult oysters normally occur at salinities between 10 and 30 psu and tolerate salinities of 2 to 40 psu (URS Greiner Woodward Clyde 1999).

In 1945, the lower CRE supported 1465 acres (593 ha) of seagrass, and no oyster reefs were documented using historical aerial photos to assess that acreage. By 1982, seagrass acreage had declined to only 182 acres (74 ha), a loss of 87% (Harris et al. 1983). By 1999, seagrass beds had further declined, covering only 2.5 acres (1 ha; Corbett et al. 2005). In 1993, *Vallisneria* beds covered roughly 1000 acres (405 ha) along the shore of the upper CRE, in a band that was located between 20 and 7 mi (32 and 12 km) upstream of Shell Point, corresponding to the region where salinity rarely averaged over 10 psu (Hoffacker 1994, as reported in Doering et al. 2002). Beginning around 2000, periods of low flow led to the loss of most of the *Vallisneria* beds in the CRE, and subsequent revegetation, when salinity conditions are appropriate, has been hampered by lack of dispersal. In 2011, surveys identified 3119 acres (1262 ha) of SAV in the CRE (Dial

Cordry and Associates 2011); almost all of the SAV coverage was in the lower reaches of the CRE where salinity would preclude *V. americana*, but support seagrasses (Figure III-2).

Oyster reefs are also likely impacted by releases of Lake Okeechobee water into the CRE, as well as by other activities such as removal by dredging to increase navigability. In 2011, there were 846 acres (342 ha) of oyster reef in the CRE (Dial Cordry and Associates 2011; Figure III-2). Low salinity (<6 psu) suppresses reproductive activity in adult oysters (reviewed in Shumway 1996), and regulatory releases of freshwater into the CRE decreases gonadal activity of oysters (Volety et al. 2009). On the other hand, single events that reduce salinities from mesohaline to oligohaline can decrease the rate of infection of oysters in the CRE by the parasite *Perkinsus marinus*, and it is likely that regular freshets related to water releases from Lake Okeechobee could contribute to better oyster body condition and lower infection rate (La Peyre et al. 2003).





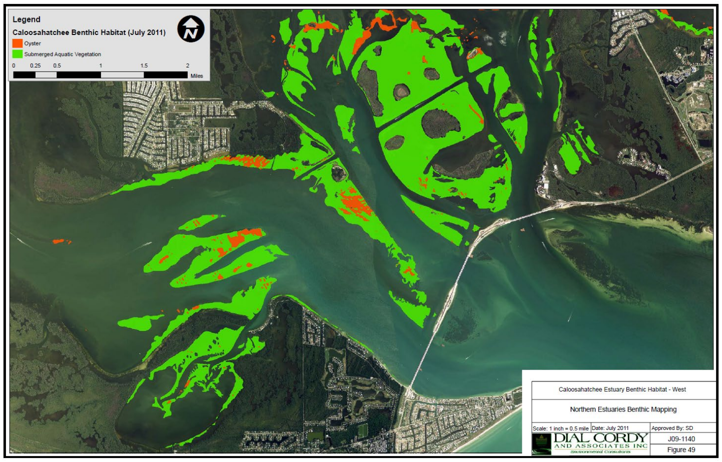


Figure III-2. Current distribution (2011) of submerged aquatic vegetation (SAV; seagrasses in the western stretches and *Valisneria americana* in the eastern stretches) and oyster beds in the CRE. Figures produced by Dial Cordry and Associates (2011). Top left: east region; Top right: East-central region, Middle row: West central region); Bottom Row: West region. SAV in green, Oysters in orange.

High river discharges in the CRE have been associated with increased nuisance stranding of macroalgae on the beaches of Sanibel, and some of the species of algae stranding on those beaches originate in the CRE (Milbrandt et al. 2019), demonstrating that CRE discharge influences the near-shore water quality in the Gulf of Mexico. Given that the growth rates of the CRE macroalgae are N-limited (Milbrandt et al. 2019), and that the macroalgae originating in the CRE has a recognizable $\delta^{15}N$ signature consistent with anthropogenic N sources (Lapointe and Bedford 2007; Milbrandt et al. 2019), it is very likely that increased N loading accompanying high discharge into the CRE fuels macroalgal blooms that are subsequently transported to the Gulf of Mexico. Discharges of nutrients from the CRE, as well from Tampa Bay and Charlotte Harbor, can contribute to the loading necessary to support red tide blooms on the Southwest Florida Shelf (Vargo et al. 2008) and harmful algal blooms (HABs) in the CRE (Paerl et al. 2008).

Discharges from Lake Okeechobee contribute significantly to nutrient loading into the CRE (Julian and Osborne 2018). Total mean annual loadings of nutrients during the period 1979-2016, via the Caloosahatchee River/C-43 through S-79 into the CRE, were 224 ± 18 metric tons (mt) TP and 2,600 ± 200 mt TN. Lake Okeechobee releases into the C-43 through the S77 averaged 64 ± 11 mt TP and 1,200 ± 0.2 mt TN. The Caloosahatchee River watershed between S-77 and S-79 is largely agricultural, and additional water, N and P are discharged into the Caloosahatchee River before it flows through the S-79 into the CRE. As the Caloosahatchee River flows through the C43 watershed, additional N and P are added to the river from the watershed. However, making the simplifying assumption that N and P discharged from the lake into the C43 watershed flowed without interaction down the C-43 to S-79, lake discharges are responsible for 22% of the P and

32% of the N that flows into the CRE. Given that only 15.3% of the total loading to the CRE comes from sources below S-79 (FDEP 2009), controlling N inputs to the CRE from Lake Okeechobee releases, as well as limiting nutrient runoff from the C43 basin, would be effective ways to reduce loading of the limiting nutrient into this N-limited estuary.

St. Lucie Estuary

The opening and stabilization of the St. Lucie Inlet between 1892 and 1897 fundamentally changed the nature of ecological communities of the SLE (SFWMD 2002; SFWMD 2002 Appendix C; USACE 2004). Before the opening and stabilization of the St. Lucie Inlet, the SLE was not an estuary (SFWMD 2002). It was fresh throughout its length and likely contained expansive beds of *Vallisneria americana.*

Once the St. Lucie Inlet was opened, the lower end of the St. Lucie River became brackish (USACE 2004), and the SLE came to support a rich and diverse estuarine flora and fauna (Chamberlain and Hayward 1996). In 1916, the C-44 canal connected the South Fork of the SLE to Lake Okeechobee. In combination, a series of projects expanded the natural watershed by about a factor of three from its original 260 mi^2 (SFWMD 2002; SFWMD 2002 Appendix C; USACE 2004; Van Horn 2019) (Figure III-3). As a result, a highly variable salinity regime and high nutrient loads have turned the SLE into a plankton-dominated estuary that only supports extremely euryhaline benthic organisms, with the historic SAV and oyster communities largely displaced (Chamberlain and Hayward 1996; Lapointe et al. 2012).

Historic St. Lucie Watershed Current St. Lucie Watershed

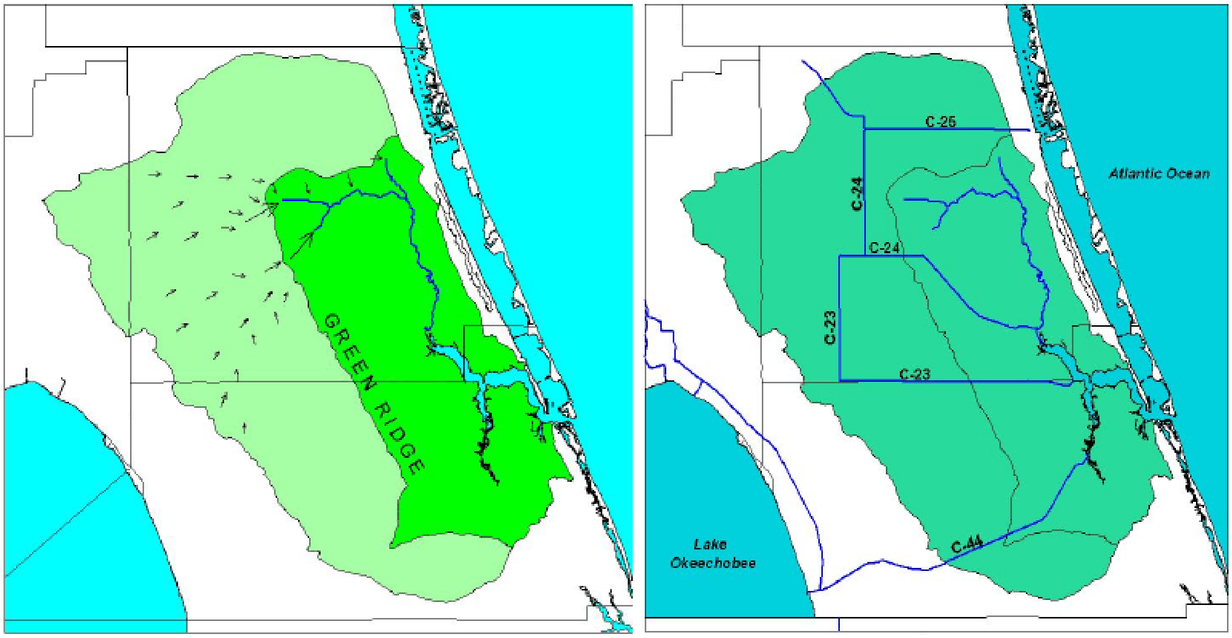


Figure III-3. Changes in the watershed of the St. Lucie system (figure from Gorman 2019 presentation). Note the canals, in blue in the right panel, that connect the watershed of Lake Okeechobee to the historic watershed of the SLE through managed freshwater discharges.

The SLE is stressed by excess freshwater during wet seasons, too little water during extremely dry periods, nutrient loads that promote phytoplankton blooms, frequent periods of low concentrations of dissolved oxygen, light limitation of the growth of primary producers caused by color, turbidity from resuspension of fine-grain sediments and phytoplankton blooms, and replacement of vegetation along the shoreline with seawalls and docks (Chamberlain and Hayward 1996; Doering 1996; Haunert and Startzman 1985; FDEP 2008). In addition, sediments in the SLE contain heavy metals at concentrations that are potentially harmful to fish and benthic macroinvertebrates (Haunert 1988). Unfavorable salinity regimes during high discharges of freshwater and increased accumulation of unconsolidated sediments have reduced the growth of oysters and nearly eliminated seagrass beds (Chamberlain and Hayward 1996; Doering 1996). For example, in 1940, beds of shoal grass (*Halodule wrightii*), Johnson's seagrass (*Halophila johnsonii*), and paddle grass (*Halophila decipiens*) were found from the mouth of the SLE upstream into the North Fork of the SLE (URS Greiner Woodward Clyde 1999) (Figure III-4). Currently, SAV occurs in small, isolated patches: 2011 benthic surveys (Dial Cordry and Associates 2011) identified only 12 acres (5 ha) of SAV beds in the SLE (Figure III-5).

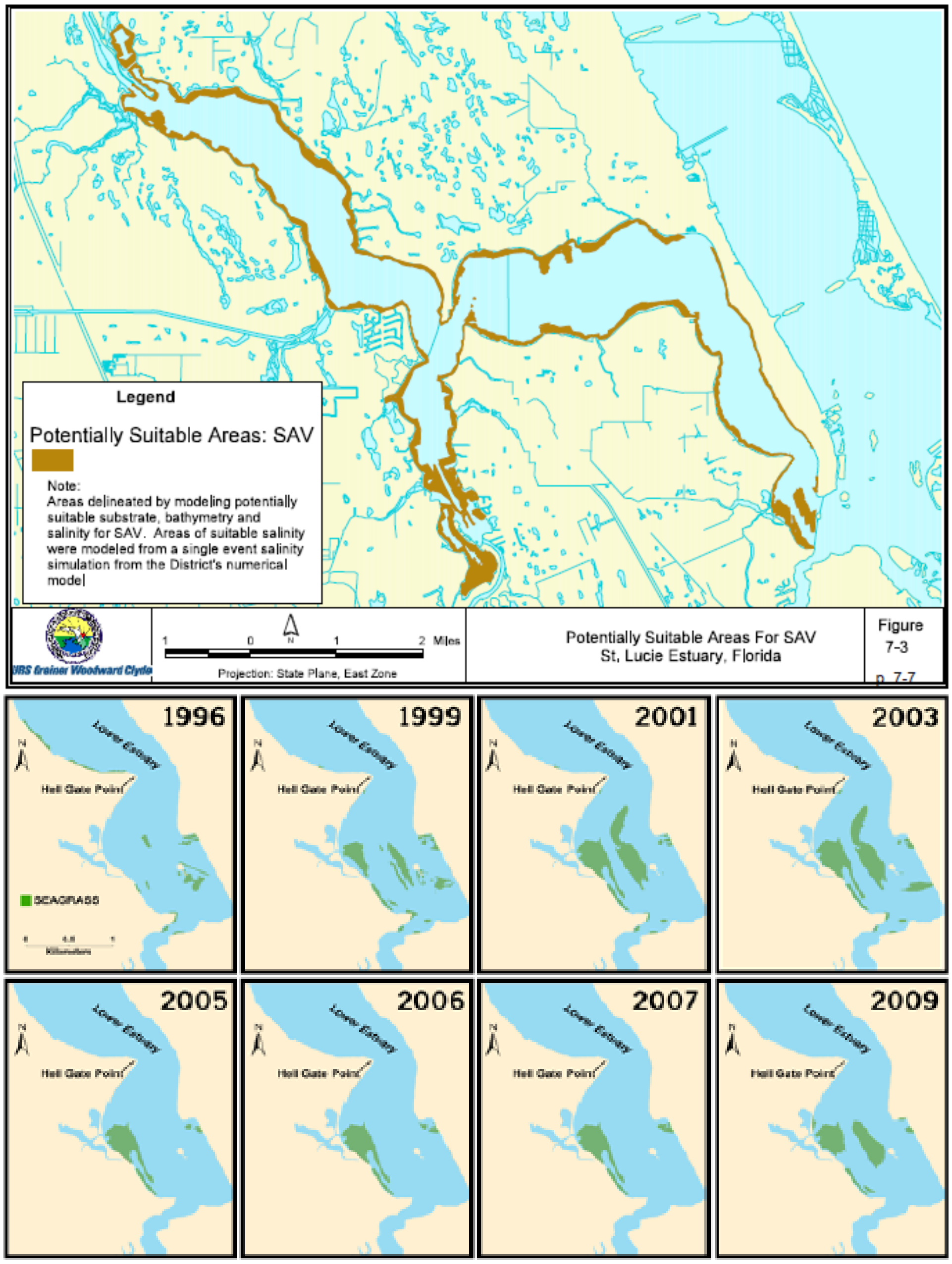


Figure III-4. Potential and recent distribution of submerged aquatic vegetation in the St. Lucie Estuary. (Figures from URS Greiner Woodward Clyde 1999 and SFWMD 2012).

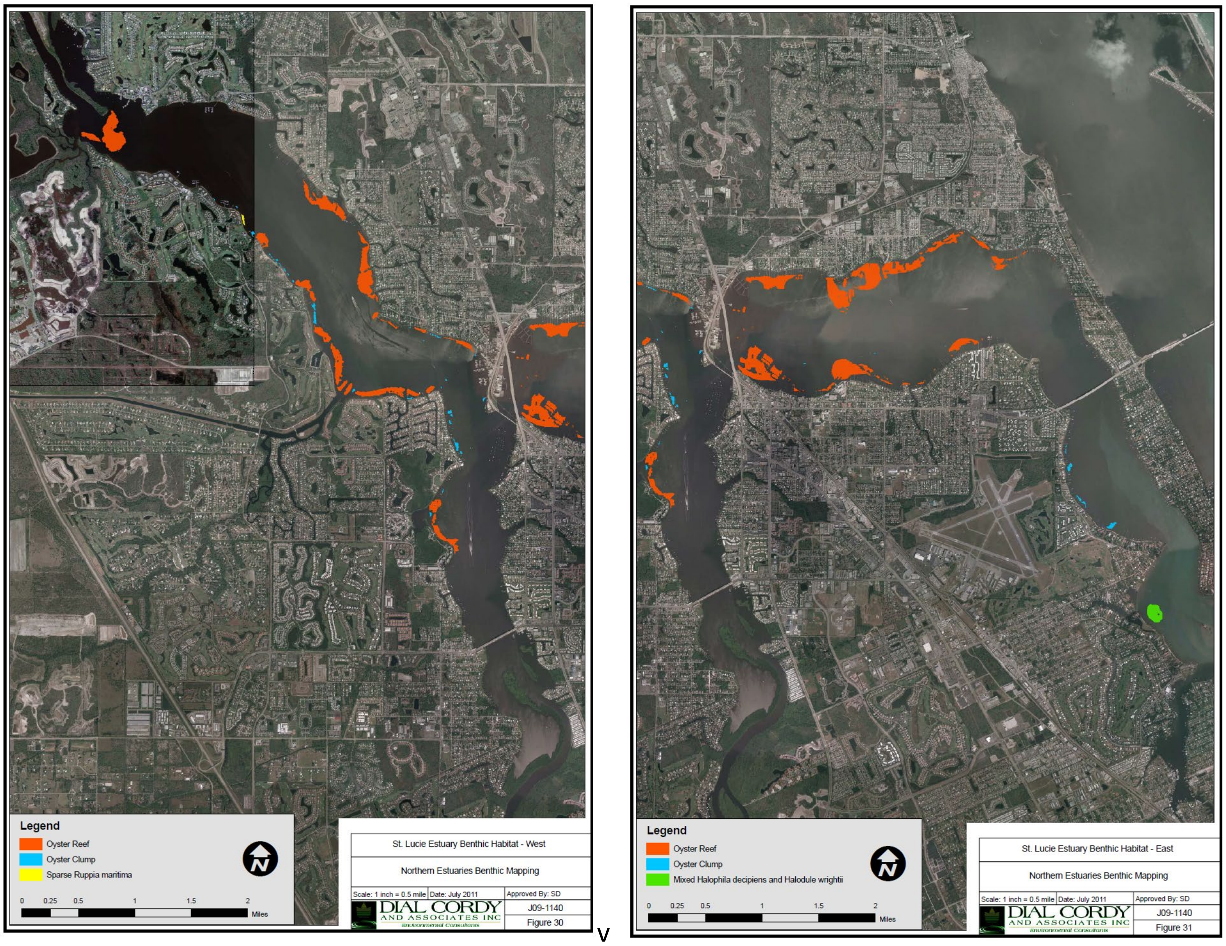


Figure III-5. Current distribution of submerged aquatic vegetation and oyster beds in the SLE. Figures produced by Dial Cordry and Associates (2011). Left panel: Western reaches; Right panel: Eastern reaches. Oyster reefs in orange; oyster clumps in blue; *Ruppia maritima* in yellow, and mixed species SAV (*Halodule wrightii* and *Halophila decipiens*) in green.

High flows and consequent low salinities also lead to mortality for oysters in the SLE. At one time, oysters covered an area of nearly 1,400 acres (567 ha) in the SLE (SFWMD 2008 Appendix A), but by 1997, 85% of that cover was lost, which left only 207 acres (84 ha) of oyster habitat (SFWMD 2008 Appendix A). A resurvey using visual observations and hydroacoustic techniques found 347 acres (140 ha) in the SLE (Dial Cordy and Associates 2011), (Figure III-5). Based on bathymetry, salinity, and substrate suitability, oysters could occur in the upper and middle estuary (URS Greiner Woodward Clyde 1999, Figure III-6). Although oysters may reach a sexually mature stage within one growing season, significant reproduction capability requires two to three years to develop, so prime areas would need to be protected from high mortality events for at least this interval to maintain a sustainable population (URS Greiner Woodward Clyde 1999).

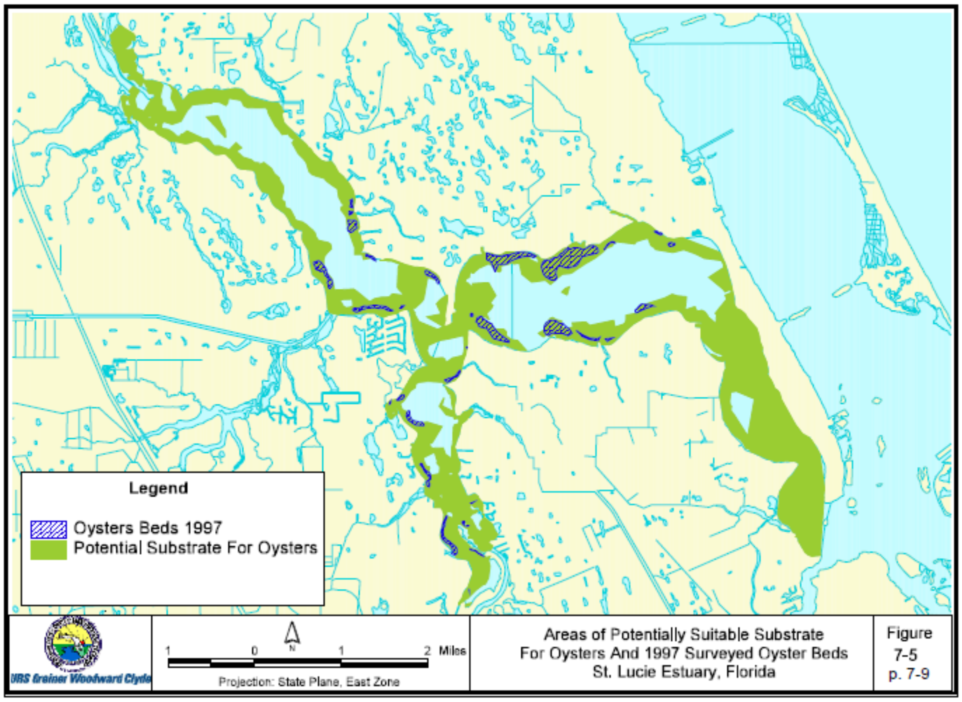


Figure III-6. Potential distribution of oysters in the St. Lucie Estuary. (Figure from URS Greiner Woodward Clyde 1999).

Protecting oysters may conflict with protecting other valued resources, with exceptionally low flows during dry periods failing to supply the base flow that supports commercially and recreationally important fish species, such as snook, tarpon, sea trout and redfish (SFWMD 2002).

In addition to changing the quantity, timing, and distribution of water, watershed modifications have affected the quality of water reaching the SLE. Historically, nutrients to support primary production were derived principally from rainfall falling within the watershed to these local sources, and concentrations in the resulting sheet flow were reduced via uptake by vegetation and binding to soils before runoff water entered the river or estuary (USACE 2004). The higher vegetation and periphyton in the system were adapted to survive under these low-nutrient conditions (USACE 2004). With the more rapid and direct delivery of local runoff, N and P loads to the estuary have been estimated to be 200% and 100% higher, respectively (USACE 2004). In addition to these increased local sources of water and nutrients, releases from Lake Okeechobee deliver additional water, P, and N to the SLE (Van Horn 2019). On average, these Lake releases account for approximately 30% of the flow of water, 23% of the P load, and 36% of the N load to the estuary (Van Horn 2019). The nutrients, and in some instances, cyanobacterial HAB blooms that reach SLE via Lake Okeechobee releases can augment local nutrient sources to drive plankton blooms in the estuary that prevent light from reaching the benthic ecological communities or attenuate light directly. Increased N availability drives plankton growth in the SLE (Kramer et al. 2018). Work from 1989 to 1991 indicated N limitation, especially during periods of high flow, because P was delivered in eroded soils (Chamberlain and Hayward 1996). Ten Mile Creek, a tributary of the North Prong, was N limited over a period of 5 months in 2006 (Lin et al. 2008), with N:P = 5.8, far below the 16:1 threshold, and the presence of nitrogen-fixing cyanobacteria was considered evidence of N limitation (Badylak et al. 2016). In 2007 and 2008, bioassays indicated general N limitation of phytoplankton was high (Phlips et al. 2012). Thus, it is clear that N loading in the SLE has contributed to the turbid, plankton-dominated current state of the estuary.

Harmful Algal Blooms (HABs) in the CRE and SLE

In addition to generally stimulating phytoplankton growth in the CRE and SLE, nutrient enrichment of the CRE and SLE can drive HABs. Two main types of HABs have been studied in the greater Everglades: those caused by *Dolichospermum circinale* (formerly known as *Anabaena circinalis*) and those caused by *Microcystis aeruginosa*. Blooms of both of these cyanobacteria can cause several environmental problems, including bad odor and bottom-layer hypoxia; however, the problem of greatest concern is the production of cyanotoxins. *Microcytis* produces both neurotoxins (including a neurotoxin responsible for paralytic shellfish poisoning, PSP) and hepatotoxins known as microcystins (reviewed in Harke et al. 2016), and *Dolichospermum* has recently been shown to produce microcystins as well (Dreher et al. 2019). Microcystins can cause fish kills and other wildlife deaths, as well as livestock poisoning and human illness or death in those who use impaired water resources for drinking water supplies, recreational activities, and fisheries. Microcystins can also accumulate in fish, birds, reptiles and mammals in aquatic and estuarine food webs that are harvested for human consumption, potentially exposing consumers of these animals to health risks (Cheng et al. 2009)

Both of these cyanobacteria produce HABs in Lake Okeechobee, and regulatory water releases from the lake introduce them into the St. Lucie and Caloosahatchee Rivers (Rosen et al. 2018). Water containing these cyanobacteria also has elevated nutrient concentrations, which may trigger blooms in the receiving water bodies (Phlips et al., in review). Both HAB species can survive when freshwater from lake releases mixes with estuarine water (Rosen et al. 2018), but salinity above 7.5 psu is toxic to *Dolichospermum*. *Microcystis* can survive salinities up to 18 psu, above which the cells lose membrane integrity, die and release the mycrosystin toxin into the water. Increasing salinity has been implicated in greater production of the microsystin toxin within *Microcystis* cells. In both 2005 (Phlips et al. 2012) and 2016 (Rosen et al. 2018), there were extensive HABs in the SLE; the 2016 event prompted the Governor of Florida to issue a state of emergency because of the human health risks associated with the blooms. While water releases containing HAB species contribute to HABs in the northern estuaries, increased flows free of the HAB species can decrease HABs that originate within the estuaries because higher flows reduce water residence time (Table III-1) within the estuaries. As a result, blooms are prevented from becoming dense before being flushed out of the system (Phlips et al., in review).

Northern Estuary Performance Measures and Ecological Targets Used in Planning and Operations of LORS2008

Currently, most surface waters in Florida, including those in the Caloosahatchee and St. Lucie Basins, are categorized as Class III waters, meaning that they must be suitable for recreation and must support the propagation and maintenance of a healthy, well-balanced population of fish and wildlife (FDEP 2012).

Estuaries are spatially and temporally complex systems that support a diverse array of species and ecological functions; therefore, choosing what components of those estuaries to monitor and build management success criteria around is a difficult problem. In the northern estuaries, the Valued Ecosystem Component (VEC) approach identified key resources provided by the estuaries (SFWMD 2008 Appendix 12-1), which were used to set management goals. The approach assumed that maintaining or enhancing prominent and valued foundational species (*sensu* Dayton 1972) would, in turn, enhance the entire community. The approach also recognized that an estuary cannot be managed to furnish ideal conditions for all species. Thus, the VEC approach focused on sustaining critical estuarine habitats created by plants or animals, with one or more species being prominent (Doering et al. 2002; Chamberlain and Doering 1998; SFWMD 2006).

Research established that a mesohaline environment is critical to the health of salinity-sensitive biota, including oysters, submerged aquatic vegetation, and juvenile and marine fish and shellfish (e.g., Haunert and Startzman 1985). The VEC process recognized three ecological communities that are dependent on specific salinity regimes as particularly important to the northern estuaries: communities of freshwater to oligohaline *Vallisneria americana* beds, oyster beds, and seagrass communities in the more downstream reaches of the estuaries. The selection of these habitats for the focus of freshwater discharge planning and operations of LORS2008 was necessarily a selection of but a few of the many biologically and ecologically important components of these estuaries.

Ecological targets, or desired conditions, for the estuaries were established during the CERP process and formalized in the Northern Estuaries Performance Measure documentation sheet (RECOVER 2007). Knowledge about the salinity tolerances of the VECs and hydrological models that relate salinity in the northern estuaries to Lake Okeechobee stage and releases were then used to set Hydrologic Targets that set the performance measures for the Lake Okeechobee Release Schedule. It is important to note that only information on the effects of water budget on salinity, the organisms' response to salinity, and a desired spatial pattern in estuarine salinity, were used to set the ecological, and subsequently, the hydrological targets and performance measures. Specifically, the estuary-specific ecological targets are:

> CRE: Re-establish a salinity range favorable to juvenile marine fish, shellfish, oysters and submerged aquatic vegetation (SAV). Re-establish consistent, clear, clean, freshwater flows that maintain low salinities in the upper estuary. Re-establish more stable salinities and ranges in the lower estuary that the seagrasses can tolerate.
>
> SLE: Maintain a salinity range favorable to fish, oysters and submerged aquatic vegetation (SAV), which necessarily requires addressing high-volume, long-duration discharge events from Lake Okeechobee, the C-23 and C-24 watersheds.

From these ecological targets, the following estuary-specific predictive hydrological targets and performance measures were defined (RECOVER 2007).

<u>Caloosahatchee River Estuary</u>

The target and performance measures for the CRE were based on optimization of hydrological model outputs, natural variation that would occur during the period 1965-2000, and desirable salinity conditions for existing and potential aquatic resources within the CRE. Targets were developed to 1) reduce minimum discharge events that would lead to high salinities in the *Vallisneria* beds upstream, 2) reduce high-flow events to the estuary to maintain an estuarine salinity regime to protect and enhance estuarine habitat and biota, and 3) acknowledge the importance of timing of flows to estuarine condition.

Seagrass and submerged mesohaline (salinity <10 psu) and oligohaline (salinity < 3 psu) plant communities have been historically important features of the CRE, and the restoration and preservation of such communities is one of the explicit goals of the Comprehensive Everglades Restoration Plan (CERP; USACE and SFWMD 2010). Using laboratory studies of salinity tolerances for the seagrass *Halodule wrightii* and *Vallisneria americana*, coupled with statistical relationships between S-79 discharge and salinities in the regions of the CRE that supported these two species, Doering et al. (2002) suggested that minimum discharges from S-79 of 300 cfs (8.5 $m^3 s^{-1}$) were needed to maintain salinity low enough (<10 psu) to support *V. americana* in the upper reaches of the CRE. Similarly, the analysis indicated that discharges less than 2800 cfs (79 $m^3 s^{-1}$) were needed to prevent lethal low salinity (<6 psu) for *H. wrightii* in the lower reaches of the CRE. The LORS2008 salinity performance measure for protecting the seagrass and *V. americana* beds in the CRE specifies maintaining minimum freshwater flows into the CRE from all sources, including the local basin, above 450 cfs (12.7 m^3 s^{-1}) and maximizing the duration of the period that the S-79 discharge is in the range 450 – 2800 cfs (12.7 - 79 m^3 s^{-1}).

Volety et al. (2003), as cited in Volety et al. (2009), suggested that salinity and flow targets similar to those for SAV would protect and enhance oysters around Shell Point and San Carlos Bay in the outer CRE. They indicated that the greatest threat to oysters is high flows for more than 2-4 weeks. Volety et al. (2009) recommended that minimizing daily discharge volume, the number of days of discharge and the durations of discharge, would be best for oyster reefs in the CRE.

Specific Performance Measures for the CRE:

- Low Flow: From October to July, no mean monthly inflows from the Caloosahatchee watershed, as measured at S79, are below a low-flow limit of 450 cfs (12.7 m^3 s^{-1}) (C-43 basin runoff and Lake Okeechobee regulatory releases).
- High Flow: No mean monthly flows exceed 2,800 cfs (79.3 m^3 s^{-1}), as measured at the S79, from Lake Okeechobee regulatory releases in combination with flows from the Caloosahatchee River (C-43) basin.
- Frequency of Flows: The frequency distribution of monthly average freshwater inflows through S-79 for the entire period of record was determined to be important for protecting and restoring estuarine resources, while further promoting biotic diversity. Approximately 75% of the flows from S-79 should be in the 450-800 cfs (12.7 - 22.6 m^3 s^{-1}) range and most of the remaining inflow should be in the 800 to 2800 cfs (22.6 - 79.3 m^3 s^{-1}) range.
- Lake Okeechobee Regulatory Release: The alternative with the least daily discharge volume, the fewest number of total days of discharge, and the fewest number of consecutive days with discharge is preferred. Special consideration is provided for pulse releases that may benefit the estuary.
- Tape Grass and Seagrass: To protect seagrasses, maintain salinity > 20 psu and maximize water clarity at the mouth of the CRE; conditions of salinities < 10 psu or water with < 5% of surface irradiance that reaches the bottom are not to exceed a time period of more than 1 week. To protect upstream *Vallisneria* beds, maintain low salinities < 10 psu and maximize water clarity, and allow no continuous time periods of salinities > 20 psu. The restoration goal of 100% tape grass, turtle grass or manatee grass coverage to -3 m mean low water (mlw) was set.

St. Lucie River Estuary

In the SLE, high flows cause unfavorably low salinities for the oysters and seagrasses (estuarine VECs). Models that incorporated freshwater discharge, watershed hydrology, estuary salinity, and biological stresses on oysters, were used to explore Lake Okeechobee discharge operations that would protect the desired distribution of seagrasses and oysters in the estuary and the southern Indian River Lagoon. Results showed that inflows exceeding 2,000 to 3,000 cfs (56.6 - 84.9 $m^3 s^{-1}$) cause unfavorable salinity regimes for oysters in their historical, mid-estuary locations. Overall, research suggests that to protect oysters, salinity should not decrease below 7 psu at the U.S. Highway 1 bridge, the point at which the majority of inflows are integrated to the system. To achieve this goal, inflows from the watershed, groundwater, and releases from Lake Okeechobee should not exceed about 2,000 cfs (56.6 $m^3 s^{-1}$; SFWMD 2009).

It was argued (SFWMD 2009) that if salinity requirements of oysters were met in the middle estuary, seagrasses with similar requirements should thrive. Widgeon grass (*Ruppia maritima*) is the most likely SAV species to be successful in the lower salinity conditions of the North and South Forks, and the middle estuary most likely will support SAV species such as shoal grass and Johnson's seagrass. The higher salinity and clearer water of the lower estuary should support shoal and Johnson's seagrasses, and perhaps manatee grass (*Syringodium filiforme*; as observed by Phillips and Ingle 1960). Nevertheless, the SAV responds to both the quantity (salinity) and quality (nutrients and water clarity) of water in the system. Managers have identified a desired target depth of about 3.3 ft (1 m) for SAV restoration in the estuary (Figure III-7 from SJRWMD and SFWMD 1994). Such a distribution can be possible only if light attenuation in the water column, controlled by sediment load, plankton, and dissolved color, is low enough to allow ≥ 20% of surface irradiance to reach the bottom (Gallegos and Kenworthy 1996). Phytoplankton in the water absorb light before it reaches the bottom, and plankton communities of SLE are N-limited (Lin et al. 2008; Yang et al. 2008; Phlips et al. 2012; Kramer et al. 2018); therefore, the depth target can be achieved only if N loads to the SLE are reduced to the point that plankton blooms are abated and if other sources of light attenuation, such as dissolved color, don't prevent sufficient light from reaching the bottom.

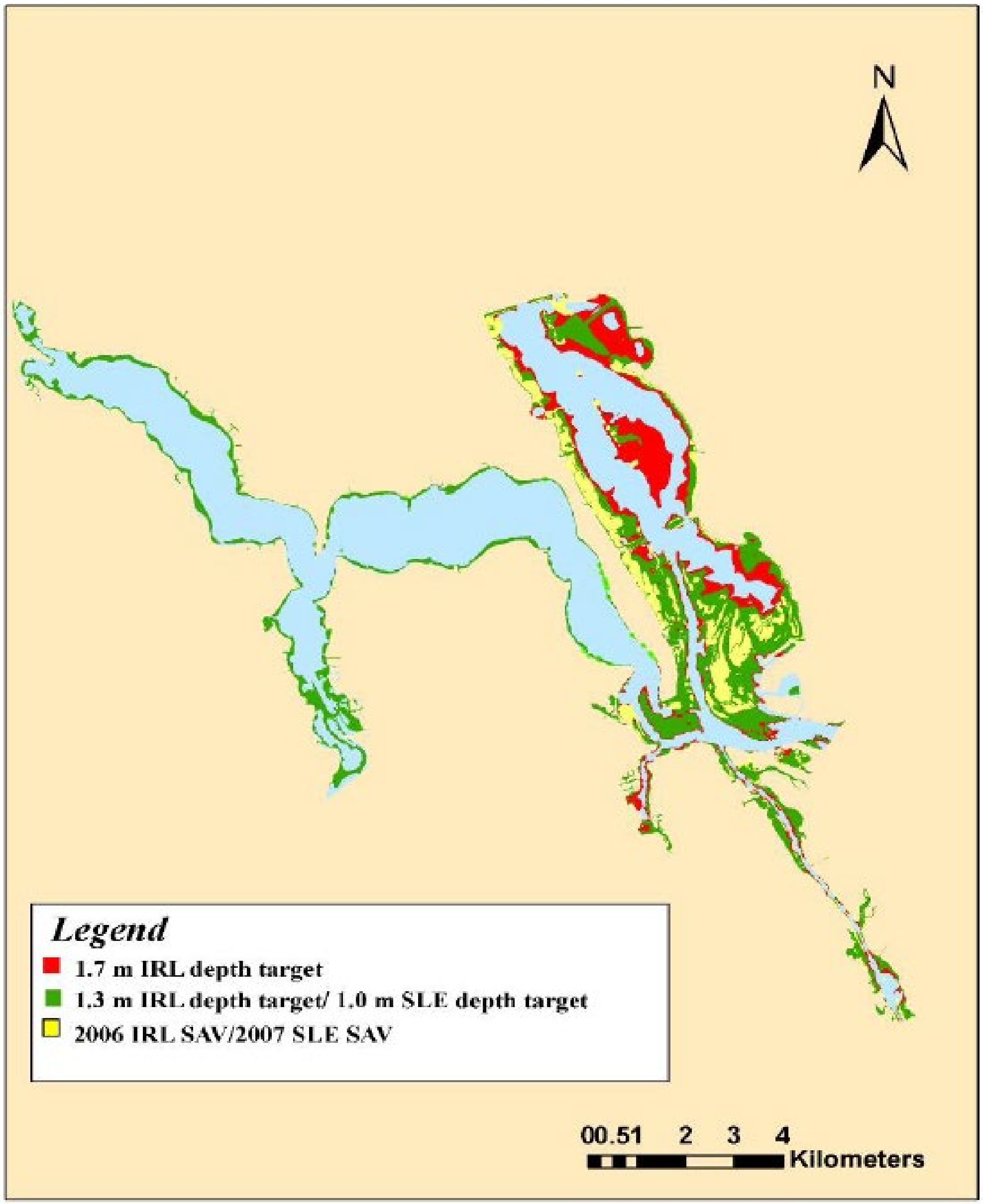


Figure III-7. Potential SAV depth targets and 2006/2007 SAV Distribution (Figure 12.5 from SJRWMD and SFWMD 1994).

The target and performance measures for the SLE were established based on extensive SFWMD monitoring of the SLE and the flows and loads from the associated basins and Lake Okeechobee (RECOVER 2007). Flows were classed into sized flow events and flow events were subsequently correlated to representative median salinities achieved at the Roosevelt Bridge, where US Highway 1 crosses the SLE. A discharge/salinity relationship was established for very low salinities using these classifications. Flow ranges of 725-3,280 cfs (20.5-92.9 $m^3 s^{-1}$) produced salinities that ranged from 1 to 5 psu. Flows of 2,000 cfs (56.6 $m^3 s^{-1}$), the mid-range of this flow class, would result in a salinity of 3 psu, a salinity implicated in the oyster mortality of 1998 and 1999. Kenworthy and Dipiero (1991) found that such low salinities would result in *Halodule wrightii* mortality. Therefore, 3 psu and 2,000 cfs (56.6 $m^3 s^{-1}$) were assumed to be threshold values for seagrass survival.

Evaluation targets were developed from natural systems modeling of the Indian River Lagoon (NSM-IRL) from the Hydrologic Simulation Program Fortran (HSPF) and historic flow data using the 1965-2000, 36-year rainfall period of record. The target salinity gradients in St. Lucie Estuary were determined by a hydrodynamic salinity model (Morris 1987), combined with estimates of salinity requirements for two indicator species in the estuary: shoal grass (*Halodule wrightii*) and American oyster (*Crassostrea virginica*). Based on the ecological restoration goals and the influence of salinity on the VECs, the salinity envelope target at the Roosevelt Bridge (mid-estuary) is a salinity range of 12-20 psu. Using this information, both interim and long-term performance measures were identified.

<u>Specific Performance Measures for the SLE:</u>

The interim target flow numbers are as follows (as number of times the condition is met in the 36-year simulation period):

- 63 months of mean flow < 350 cfs (9.9 $m^3 s^{-1}$).
- 24 Lake Okeechobee regulatory discharge events (14 day moving averages > 2,000 cfs (56.6 $m^3 s^{-1}$))
- 36 Local basin flow > 2,000 cfs (56.6 $m^3 s^{-1}$) (based upon 14 day moving averages > 2,000 cfs (56.6 $m^3 s^{-1}$))

Full restoration targets are estimated to be (as number of times the condition is met in the 36-year simulation period):

- 31 months of mean flow < 350 cfs (9.9 $m^3 s^{-1}$).
- 0 Lake Okeechobee regulatory discharge events (14 day moving averages > 2,000 cfs (56.6 $m^3 s^{-1}$))
- 28 Local basin flow > 2,000 cfs (based upon 14 day moving averages > 2,000 cfs (56.6 $m^3 s^{-1}$))
- No more than 12 months of mean monthly flow > 2,000 cfs (56.6 $m^3 s^{-1}$), based upon the assumption that flows in excess of 2,000 cfs (56.6 $m^3 s^{-1}$) produce salinities below 3 psu at Roosevelt Bridge.

Current Monitoring to Assess Performance Measures in the Northern Estuaries

Currently, the response of the northern estuaries to water management activities is being assessed through monitoring the status of the identified VECs (*Vallisneria*, seagrasses and oysters) in the estuaries. Additional monitoring in the CRE beginning FY20 will assess a new proposed indicator species (the clam *Rangia cuneata),* ichthyoplankton and zooplankton communities and POM and chlorophyll a gradients along the estuary as part of the Recovery Strategy monitoring plan (Personal communication, A. Kahn, SFWMD, Dec 30, 2019).

In the CRE, oyster status is monitored at six sites in the lower estuary. Water quality variables of temperature, salinity, pH and dissolved oxygen (DO) concentrations are measured monthly at the six sites. Also monthly, oysters from each site are collected for analysis of gonadal condition and general condition, juvenile oyster survival and oyster spat recruitment. On a bi-annual basis, the density of adult oysters is determined with quadrat counts at all sites, and at select sites, quarterly. Although this program is excellent at tracking the conditions of oysters from the six monitoring sites, it does not provide sufficient data to predict likely future trends in site-specific oyster populations, nor does it track the expansion or contraction of the area of the estuary that is colonized by oysters.

Submerged aquatic vegetation is monitored by a number of programs in the CRE using a variety of in-water, hydro-acoustic and remote sensing techniques. In-water sampling is done at fewer than a dozen sites within the main stem of the CRE, whereas there are more sites in San Carlos Bay, Pine Island Sound and Matlacha Pass, seaward of the CRE. In-water surveys document species composition and abundance of the SAV. Most of the programs collect basic data on the water column (water clarity, salinity and DO), but more detailed information on the water quality that drives SAV health is not well-assessed.

Twice a year, SAV species cover, abundance and canopy height; water quality parameters; and light attenuation are measured at random points (at <2m depth) throughout the entire South Indian River Lagoon/SLE and the CRE. Additionally, in each estuary there are permanent transects (3 transects per site, multiple sites per estuary) along which cover, shoot density, and canopy height are measured monthly during the summer and every other month the remainder of the year, and occasional cores are collected for analyses of above- and below-ground biomass. Water quality variables and light attenuation are also measured. Additionally, research is being done to test biomarkers (e.g., stress enzymes) on oysters, *Rangia cuneata* clams, and *Valisneria americana* to assess salinity stress, which may be an additional tool for future field application.

Oysters are monitored at three sites in the SLE: in the mid-estuary, the South Fork and the North Fork. Monitoring tracks: (1) spatial and size distributions of adult oysters (twice a year at the North and South Fork sites, quarterly at the mid estuary); (2) distribution and frequency of the oyster diseases *Perkinsus marinus* ("dermo") and *Haplosporidium nelsoni* (MSX) (monthly); (3) reproduction and recruitment (monthly); and (4) juvenile oyster growth and survival.

In addition to monitoring the VECs, sedentary and long-lived benthic invertebrates are also monitored at 14 sites in the SLE; data from these collections are being analyzed using a marine biotic index approach that describes community structure. The biotic index approach can be used as another dependent variable in the analyses of lake discharge, salinity and water quality; such analyses should be used to inform water management actions.

Performance Measure Considerations for Guiding Future Water Management Decisions

The northern estuary performance measures for assessing ecosystem restoration and for guiding Lake Okeechobee releases were largely developed from a solid body of research regarding the salinity tolerance of a few, important, foundational oligohaline and estuarine species, the desire to preserve the distribution of these foundational species along the estuaries, the influence of lake discharges on the salinity structure of the estuaries, and predictions of salinity distributions and variability in the estuaries from hydrodynamic models. Our scientific understanding of the northern estuaries has grown since these measures were defined, and the changing state of the estuaries has made clear that this new knowledge should be used to design future planning and operations of water management in the Greater Everglades. Other important considerations, beyond the foundational species, include water quality, HABs, health of fisheries, biodiversity, species of concern and human and animal health issues. All of these factors, in addition to the use of improved hydrological and ecological models, incorporation of climate change projections into models, and improved metrics to monitor health of current VECs should be incorporated into planning and implementing the optimal water release strategies for Lake Okeechobee.

Improved Hydrological and Ecological Models

The foundational species respond to many drivers other than salinity, and the evidence is clear that nutrient loading is driving ecosystem change, with respect to the status of these foundational species and the VECs they support. Models have been developed, and more continue to be developed (e.g., HSPF and CH3D for the Caloosahatchee Watershed and Estuary, Wash123 and CH3D for the St Lucie Watershed and Estuary, and Habitat Suitability Index (HSI) models for both estuaries), that describe how multiple stressors interact to determine the distribution of the foundational species and the VECs they support. These models could be used, in conjunction with the South Florida Water Management Model (SFWMM) or the Regional Simulation Model (RSM), to move beyond discharge/salinity models (which rely on a single factor that affects the health of the estuaries) to inform selection of optimal alternatives for managing releases from Lake Okeechobee (and implementing the selected alternative),. Such models also can address the autoregressive nature of salinity regimes and explicitly simulate the importance of nutrients and organism life histories that directly relate the health of the VECs to the quality, quantity and timing of Lake Okeechobee releases (Buzzelli et al. 2015; Barnes 2005; Barnes et al. 2007).

Incorporation of Climate Change Projections into Models

It is also important to realize that previous planning related to the effects of water management activities on hydrology and ecology of the south Florida ecosystem was done using historical data on ecological state and water budgets. Doing so implicitly assumes stationarity in the drivers of the relationships between climate, sea level, and human water use on water budgets, and ecological impacts. Given that sea level is rising and global temperatures are increasing, and that these changes are predicted to lead to difficult-to-predict shifts in rainfall and evaporation, basing future operations on historical conditions is likely to lead to management that is not protective of the water and ecological resources. The hydrological and ecological models developed to guide future lake operations must incorporate the non-stationarity of the climate that is driving water budgets, rather than relying on descriptions of past patterns of sea level rise, temperature and rainfall, if those operations are to be protective of the ecological health of the estuaries.

Improved Metrics to Monitor Health of Current VECs

Reliance on salinity envelopes to target the preservation of the VECs of the northern estuaries is demonstrably insufficient to assure the health of the northern estuaries, given the recent declines in SAV and oysters, increases in nutrient loading, increases in phytoplankton abundance and increases in the prevalence of HABs. In addition, the monitoring programs in place to assess the status of the VECs in the estuaries are valuable but limited to relatively few sampling sites along the estuaries.

Furthermore, the variables that are currently measured in the northern estuaries do not provide the predictive framework needed to manage water releases from the lake adaptively and prevent future environmental harm to the estuaries. Currently, assessing the effects of Lake Okeechobee releases on the health of the estuaries relies on assessing the state of the VECs in the estuary, specifically, the areal coverage of the desired biological communities (seagrasses, oysters, and *Vallisneria*). Such monitoring of the *state* of the VECs should be augmented with monitoring of indicators of the stresses that act on these communities and could be used to predict an impending state change before it occurs. Such indicators have been particularly well developed for the seagrass VEC. Many aspects of the seagrass communities, including the plants themselves, are indicators of water quality, nutrient availability and the overall health of the system (Fourqurean and Rutten 2003, McMahon et al. 2013, Fourqurean et al. 2019), with some useful indicators being taxonomic composition, element content, and stable carbon (C) and nitrogen (N) isotope ratios. For example, species composition of seagrasses in the subtropical western Atlantic is a function of the availability of nutrients (Powell et al. 1989, 1991, Fourqurean et al. 1995) and light (Wiginton and McMillan 1979). Element stoichiometry (C:N:P ratios) of seagrass leaves serves as an indicator of relative availability of nutrients and light (Duarte 1990, Fourqurean and Rutten 2003, Campbell and Fourqurean 2009). Seagrass leaf $\delta^{13}C$ serves as an integrating indicator of light reaching the bottom (Cooper and DeNiro 1989; Abal et al. 1994; Hu et al. 2012; Campbell and Fourqurean 2009), and $\delta^{15}N$ can be used to trace the source of N being utilized by primary producers (McClelland et al. 1997). Similarly, monitoring data on oyster age, structure, physiological status, recruitment and survival should be used to generate predictions of impending change in oysters. Changes in these indicators could be used to predict how future states of the estuaries will differ from the present state based on past nutrient discharges from Lake Okeechobee and the local watersheds. Explicit ecological indicators that are predictive of the trajectory of ecosystem health should be developed for the VECs in the estuaries and these predictions should be used to plan future operations of the lake.

Additional Factors to Consider for Northern Estuary Performance Measures

In addition to the health of the VECs in the northern estuaries, there are many other valued attributes of the system that either are vital indicators of the health of the system, important ecologically and economically, protected by federal law, linked to human health concerns, or a combination of all these properties. A 2013 workshop of local experts examined the currently used performance measures for the response of CRE to water releases (Parsons 2013), and they concluded that “Overall, the indicators that have been in place for many years now (oysters, tape grass [*Vallisneria americana*], and seagrass) are providing useful and valuable data on ecosystem responses to managed flow in the Caloosahatchee. Unfortunately, the dwindling population of *Vallisneria* is severely hindering its continued use as an indicator, but perhaps restoration efforts will allow the population to rebound (especially if low salinities are better maintained and herbivory is kept in check).” Furthermore, the experts suggested multiple candidates for additional useful indicators, including “phytoplankton, zooplankton, cyanobacteria, drift algae, benthic invertebrates, fishes, oxbows, and invasive species” that can also provide valuable information about the status of the CRE, in addition to the VECs of SAV and oysters. An additional benthic indicator organism, *Rangia cuneata*, has been selected for monitoring in the CRE, which will commence in FY20, along with ichthyoplankton and zooplankton monitoring, with a focus on upstream stations and variable flow events as part of the CRE MFL Recovery Strategy.

Endangered Species Concerns

The northern estuaries are home to a number of threatened and endangered species, and therefore the impacts of water releases on these species must, by law (the Endangered Species

Act, ESA), be taken into consideration if water management activities could have deleterious impacts. Threatened and endangered species of the northern estuaries include the Florida manatee, wood stork, American crocodile, bald eagle, and Johnson's seagrass.

The Florida manatee (*Trichechus manatus latirostris*) is a federally listed threatened species that is found in the CRE and the SLE (Runge et al. 2017). Water control structures in Florida have been identified as a source of mortality for manatees, but beginning in 1994, the Florida Fish and Wildlife Conservation Commission and the Florida Department of Environmental Protection began implementing measures to reduce the number of manatee deaths associated with those structures**.** In the long term, red-tide-related mortality is the greatest threat to the probability of extinction of the manatee (Runge et al. 2017), so increasing severity of red tides related to Lake Okeechobee discharges of N, as suggested by Vargo et al. (2008), could have important impacts on this iconic species. It is also likely that other HABs (e.g., *Microcystis* blooms) in the northern estuaries, fueled by nutrient discharges into the estuaries from the lake, could also threaten manatees. In addition, loss of seagrass and *Vallisneria*, driven by salinity fluctuations and eutrophication, are significant stresses on the increasing numbers of manatees (FWC Seagrass Integrated Mapping and Monitoring Program Mapping and Monitoring Report No. 3).

The CRE is important habitat for the endangered small-toothed sawfish (*Pristis pectinata*) that use estuaries during their first few years of life. Tagged juvenile sawfish preferred stretches of the CRE with salinities from 18 to 24 psu (Simpfendorfer et al. 2011). High S-79 discharges restrict sawfish to the lower reaches of the CRE, and rapid changes in salinity associated with water management activities force large energy expenditures by sawfish and may make them more susceptible to predation (Simpfendorfer et al. 2011). Hence, future planning and operations of Lake Okeechobee releases must consider how discharges through S-79 could impact this endangered species.

The lower reaches of the SLE now support a population of the federally listed threatened species Johnson's seagrass (*Halophila johnsonii*). Listed as threatened on 14 September 1998, Johnson's seagrass became the first marine plant federally listed under the Endangered Species Act (ESA; NMFS 2002). A 2,770-acre (1,121 ha) portion of the Indian River Lagoon, just north of the St. Lucie Inlet was designated as critical habitat for the species. This species likely would not have occurred in the historic St. Lucie River because of its freshwater character before the St. Lucie Inlet was opened and stabilized. Johnson's seagrass is directly protected by provisions of the ESA under National Marine Fisheries Service (NMFS) jurisdiction. Federal agencies conducting, permitting, or funding actions that may affect Johnson's seagrass are required to consult with NMFS Protected Resources Division. Future planning of Lake Okeechobee releases should consider how those operations may impact this threatened species.

Other Economically Important Species

The northern estuaries and their VECs provide habitat for a plethora of economically and ecologically important species, and the impacts of freshwater management on many of those species should be considered in Lake Okeechobee water release planning and operations. For example, there is a large blue crab (*Callinectes sapidus*) fishery in the CRE that in 2003 employed 183 fishers who landed more than 450 metric tons of crabs. Dry season (Nov-April) discharges below 8.6-12.3 $m^3 s^{-1}$ lead to significant harm to the blue crab fishery in the following year (Doering and Wan 2018). Implications of water releases for these types of economically and ecologically important species should be included in decisions regarding lake releases. In SLE, SAV provides refuge, a nursery and a habitat for foraging to juvenile stages of recreationally important fishes (Virnstein et al. 1983; Lewis 1984). These species include mutton snapper (*Lutjanus analis*), yellowtail snapper (*Ocyurus chrysurus*), lane snapper (*Lutjanus synagris*), gag grouper (*Mycteroperca microlepis*), pinfish (*Lagodon rhomboides*), tarpon (*Megalops atlanticus*), common snook (*Centropomus undecimalis*), spotted sea trout (*Cynoscion nebulosus*), and redfish (*Sciaenops ocellatus*; Sime 2005). These juvenile fishes rely on the stenohaline and stenothermic conditions in seagrass beds, so protecting the seagrasses may be sufficient to protect these valued species (Sime 2005).

Water Quality

The quality of water released from Lake Okeechobee plays as large a role in the impacts of those releases as the quantity of water. It has long been recognized that P in the lake water released to the south causes harm to the marshes of the Everglades and has the potential to harm the P-limited waterbodies to the south. It is now abundantly clear that the quality of water released to the northern estuaries also causes environmental harm. However, unlike water released to the south, it is the N in water released to the N-limited northern estuaries that causes the harm. Anthropogenic nutrient loading from the lake watershed has caused eutrophication, leading to more than a doubling in nutrient concentrations, a decline in N:P by 50% and accumulation of massive quantities of nutrients the lake sediments (Havens et al. 1996). The biotic community in the Lake has undergone changes because of eutrophication: oligochaetes have become the dominant macrobenthos; cyanobacteria (some of the HAB species) have replaced diatoms as the dominant phytoplankton; nitrogen limitation has increased in frequency, and nitrogen-fixation has become a major route of nitrogen input (Havens et al. 1996). Without decreasing nutrient concentrations in the discharged lake water, the only way to reduce loading to the estuaries is to curtail releases of water from the lake to the estuaries. A strategy that combines reducing N concentrations and reducing releases to the estuaries during wet periods would be the best way to reduce the deleterious impacts of N loading into the sensitive northern estuaries. Potentially valuable strategies for reducing N loading from the lake include: establishing a nitrogen Total Maximum Daily Load (TMDL) and Basin Management Action Plan (BMAP) for Lake Okeechobee; managing Lake Okeechobee to increase denitrification within the lake; and/or building stormwater treatment areas east and west of the lake to remove nitrogen before water is discharged to the estuaries.

Human Health Concerns

Given the known human health impacts of HABs and the apparent increase in HABs in the estuaries, planning for future lake releases should include strategies that would minimize or eliminate HABs in the estuaries, as well as decrease the fertilizing of coastal red tide blooms with nutrients from lake releases. The economic impact of toxic algal blooms on the health of Florida citizens, and on the tourism industry, has real value that needs to be weighed against the value of economic impacts of either holding more water in the lake or directing HAB and nutrient-laden water to parts of the system other than the northern estuaries. In the current Lake Okeechobee Regulation Schedule (LORS2008), water quality (including nutrient concentrations) and harmful algal blooms are not considered in decisions to release water to the northern estuaries. However, legal considerations prompted the State of Florida Restoration Strategies Program, which utilizes constructed wetlands (Stormwater Treatment Areas, or STAs), to reduce P concentrations in water that flows south into the P-limited Everglades National Park and the southern estuaries. A nitrogen control strategy for the northern estuaries, analogous to the phosphorus control strategy for the Everglades Protection Area and Southern Estuaries, should be developed.

Recommendations

- Water quality and water quantity should be managed together in both Lake Okeechobee System Operating Manual (LOSOM) planning and LOSOM operations, acknowledging that nutrient limitation of primary production may differ in the lake, northern estuaries, Everglades Protection Area and southern estuaries. Previous northern estuary ecologic performance measures were focused heavily on ecologic impacts of water quantity, through impacts of lake discharges on estuarine salinity. Future performance measures should also take into account how nitrogen, phosphorus and algae within lake discharge water affect estuarine ecology.
- A nitrogen control strategy for the northern estuaries, analogous to Restoration Strategies for the EPA and Southern Estuaries, should be developed. This strategy could include establishing a nitrogen Total Maximum Daily Load (TMDL) and Basin Management Action Plan (BMAP) for Lake Okeechobee; investigating ways to increase *in-situ* denitrification in Lake Okeechobee; building stormwater treatment areas east and west of the lake to remove nitrogen before water is discharged to the estuaries; and/or developing and implementing new nitrogen-based performance measures for the estuaries.

- Robust monitoring programs to assess not only the state of the estuaries, but also to project their future status, should be designed and implemented. The current set of monitoring sites for the state of seagrasses, oysters and *Vallisneria* should be spatially augmented and monitored more frequently. In-situ water quality and HAB pigment sensors (e.g., Beckler et al. 2019) should be deployed and telemetered from sentinel sites. Explicit ecological indicators that are predictive of the trajectory of ecosystem health should be developed for the estuaries, and these predictions should be used in both planning and operations of the Lake Okeechobee system.
- The South Florida Water Management District (SFWMD) has developed promising hydrodynamic, water quality and ecologic modeling tools for the Northern Estuaries (e.g., HSPF and CH3D for the Caloosahatchee Watershed and Estuary, Wash123 and CH3D for the St Lucie Watershed and Estuary, and Habitat Suitability Index (HSI) models for both estuaries). These models could be used in concert with the South Florida Water Management Model and/or the Regional Simulation Model to link water quality and ecological outcomes to hydrology and water management decisions in a more rigorous, quantitative manner. Accelerated investment in these modeling tools is recommended so that they become an integral part of the planning and operations decision-making toolbox. These linked hydrologic-water quality-ecologic modeling systems could be used in the LOSOM planning process to screen alternative operating plans. They also could be used to broaden monthly analyses of operational conditions that currently include forecasts of climate and hydrologic conditions, by incorporating forecasts of water quality and ecologic conditions in the lake and estuaries.
- Remote sensing and *in situ* observations should be integrated with predictive models to forecast the onset and demise of *Microcystis* blooms in the northern estuaries in near real time (e.g., Hu and Feng 2016, Tian and Huang 2019). These models could be used to help manage water releases from the Lake.
- Under LORS2008, water quality and ecological conditions that may influence operational flexibility are discussed in weekly conference calls among agency scientists and stakeholders. The improved data and predictive tools described above could be used to incorporate water quality and ecological antecedent conditions and forecasts more quantitatively into LOSOM release guidance flowcharts when human safety is not a concern. Examples of water quality and ecological criteria that could be incorporated into LOSOM estuary release guidance flowcharts include: 1) limit lake discharges into estuaries when *Microcystis* concentrations exceed certain limits at lake outflow structures to prevent seeding algal blooms in the estuaries; 2) limit lake discharges into estuaries when total nitrogen concentrations exceed certain limits to prevent and/or mitigate eutrophication and algal blooms in the estuaries; and 3) manage lake discharges to protect endangered, commercially important and/or recreationally important species in the estuaries.

- The simplified, event-based hydrologic surrogates for estuary ecological performance measures used in LORS2008 planning should be enhanced. More sophisticated hydrologic measures should be developed that better account for the timing, duration, and frequency of events; antecedent salinity conditions in the estuaries; differences in the resilience of ecosystem components; and changing climate.
- All hydrologic, ecologic and economic performance measures should be compared systematically to observed/historic hydrologic, ecologic and economic impacts to quantitatively assess whether ecologic and economic harm is actually experienced when performance measures are not achieved.

IV. Incorporating Climate and Sea Level Information into the Next Lake Okeechobee System Operating Manual (LOSOM)

Introduction

Lake Okeechobee receives runoff from a large tributary area spanning about 5,600 sq. mi, of which the northern subbasins cover as much as 4,000 sq. miles. Contributing basins in the north include both the Upper and Lower Kissimmee, Lake Istokpoga and its tributary watersheds, Indian Prairie, Taylor Creek and Nubbin Slough, and Fisheating Creek (Figure IV-1). Many of these subbasins, which include built infrastructure for water management, contribute the majority of inflow that results from highly variable rainfall patterns. Lake Okeechobee has a surface area of approximately 730 sq. mi (>1800 km^2) and an average depth of about 9 feet (2.7 m). Large inflows from tributary basins during wet periods can raise the water level rapidly, by several feet. For instance, a mere 12 inches (0.3 m) of runoff over the basin may result in a three-to-four-ft (0.9-1.2 m) rise in lake level. Because inflow capacity exceeds outflow capacity by a substantial amount, the lake level may rise and stay high for an extended duration (multiple years) during wet periods.

Inflows vary from year to year and also exhibit multi-year and decadal patterns of variability. Therefore, the Lake Okeechobee Regulation Schedule, which attempts to balance the myriad objectives of managing lake level, storage, and freshwater discharges to the northern estuaries and Everglades Protection Area, needs to account for trends in precipitation, evaporation, lake inflows, outflows and carry-over storage over extended periods. From a hydrologic point of view, evaluation of alternatives for the Regulation Schedule requires simulation of inflows, outflows, and water levels, which has traditionally been done over the entire historical period of record for which there are reliable climate data. This exercise of designing a Regulation Schedule using the period-of-record historical data is a **Planning** task that requires continuous simulation of the hydrology of Lake Okeechobee. Evaluation of Regulation Schedule alternatives during the planning phase typically involves numerous performance metrics associated with the multiple objectives related to managing the lake (Flood Protection, Water Supply, Navigation, Lake Ecology, Northern Estuary Ecology and Greater Everglades Ecosystem Ecology).

Once a Regulation Schedule is approved, the implementation of the rules associated with it requires another scale of hydrologic analysis, namely **Operations**. Typically, the temporal scale (operational window) associated with this stage is of the order of days to months, and up to one or two seasons, covering a 12-month period. The rules for managing Lake Okeechobee level are generally displayed in various graphics and documents that accompany the Regulation Schedule, and typically, they are associated with the required magnitude of discharge at various outlet structures, depending on the lake level and other factors. Recent regulation schedules have also included inflow forecasts and outlooks as supplemental factors for making decisions during an operational window.

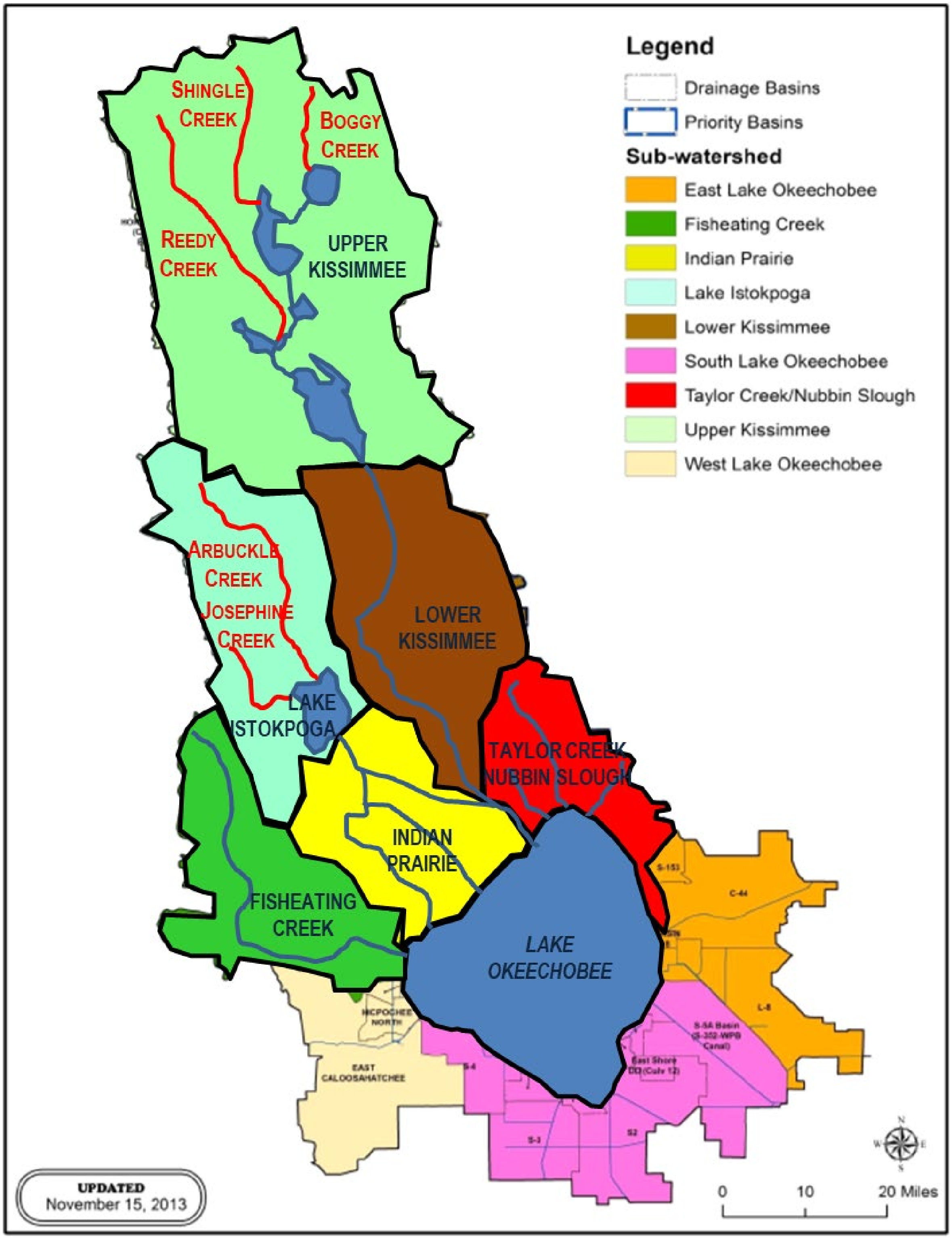


Figure IV-1. Lake Okeechobee tributary basins (SFWMD, 2014).

Climate and Hydrologic Data Required for Lake Okeechobee Regulation Schedule 2008

Climate conditions are important for both Planning and Operations phases of a Regulation Schedule development and implementation. The following sections review the role of climate variability and change, and sea level rise in both planning and operations, and present recommendations for new ways of incorporating climate and sea level information into the next Lake Okeechobee System Operating Manual (LOSOM).

As described in Chapter I, the current Lake Okeechobee Regulation Schedule, LORS2008, is a collection of complex operating rules, described in the Water Control Plan (WCP) and the Final Supplemental Environmental Impact Statement (SEIS), published in 2007 (Figure IV-2). The Operational Phase of the LORS2008 consists of several tasks, including data gathering, modeling, and decision-making through inter-agency coordination. Implementation of LORS2008 occurs on a weekly basis and there is a well-established process for data gathering and coordination.

The extensive data required to arrive at a release decision under LORS2008 include Lake Okeechobee Water Level; Tributary Hydrologic Condition (THC); Seasonal and Multi-Seasonal Outlook for Lake Okeechobee Net Inflow (LONINO); Meteorological Forecasts (up to 30 days); and Water Levels in Water Conservation Areas (WCAs) relative to their regulation schedules, potential Everglades impacts, and Stormwater Treatment Area (STA) capacity. The details of the frequency and sources of climate/hydrology input data associated with LORS2008 are provided in Table IV-1.

Table IV-1. Information required for implementing the Decision Tree in LORS2008

Climate/Hydrology Input	Time Step/Span	How it is obtained/estimated
Lake Okeechobee and WCA Levels	Daily	Observed (operations) or Simulated (planning)
Tributary Hydrologic Condition (THC)	Previous two weeks	(1) Palmer Drought Severity Index (Climate Division 4), or (2) Lake Okeechobee Net Inflow (LONIN[1])
Seasonal Climate/Hydrologic Outlook (LONINO[2])	6 months	(1) Croley's method; (2) SFWMD empirical method (USACE 2008); or (2) Subsampling of LONINO averages for years that mimic the projected state of climate indicators.
Multi-Seasonal Climate/Hydrologic Outlook (LONINO[2])	7-12 months depending on the starting month	Expected inflow for the remainder of the season plus entire six months of the next season (calculated per options above)
Up to 30-day Meteorological Forecast	30-day forecast	Shorter range meteorological and climatological forecasts (few days to 1 month)

[1] Lake Okeechobee Net Inflow, LONIN = Rainfall – Evapotranspiration (ET) + Inflow, i.e., total structural inflow + net rainfall over the lake.
[2]Lake Okeechobee Net Inflow Outlook, LONINO. Expected net gain in storage in the lake after accounting for ET.

Data gathering for the Planning and Operations phases is different. For Operations, data for Lake Okeechobee and WCA water levels are estimated from real time observations. The THC is determined as a wetter condition of two variables: (a) Weekly Palmer Drought Severity Index (PDSI) in the region upstream of Lake Okeechobee; and (b) 14-day moving average of LONIN (Rainfall – Evapotranspiration (ET) + Inflow), which is the actual inflows to Lake Okeechobee via structures plus net rainfall (Rainfall-ET) input over the lake surface. The Seasonal and Multi-Seasonal Outlooks for Lake Okeechobee Net Inflow (LONINO) can be computed using various methods (WCP 2008) including (a) Croley's method (USACE 2008); (b) SFWMD empirical method (USACE 2008); or (c) Subsampling of LONINO averages for years that mimic the projected state of climate indicators such as the Atlantic Multidecadal Oscillation (AMO) and El Niño Southern Oscillation (ENSO) (see next section). The first two methods are based on the climate outlook produced by the Climate Prediction Center (CPC).

For the Planning phase, water levels of both Lake Okeechobee and the WCAs, required for implementing the release guidance flowcharts, are obtained from simulation runs of the South Florida Water Management Model (SFWMM). However, complete time series of THC, LONINO, and 30-day forecasts, needed to drive the SFWMM, must be assembled prior to making the period of record modeling runs. These time series are developed using historical data, hindcasts of teleconnections such as El Niño and AMO, and the historical LONIN values. The use of hindcasts during the Planning phase is intended to mimic what would happen during the actual operations, but it also assumes that hydrological, climatological and weather patterns will be the same during the future planning period as they were in the historical data record.

Under normal conditions, Parts A through D of LORS2008 (Figure IV-2) produce a range of allowable lake releases. Additional operational considerations include occasional release guidance known as Adaptive Protocols (AP) (SFWMD 2010) that may be used by SFWMD to consider baseflow and environmental water supply. The weekly decision-making process includes (a) Tuesday conference calls among the scientists to gather input from all the agencies, stakeholders and the public; (b) a Wednesday conference call among the USACE-SFWMD Water Managers; (c) a recommendation by SFWMD to the USACE; and (d) a recommendation by USACE to its leadership. The final decision by the USACE leadership is implemented for the following 7-day period and this weekly process continues.

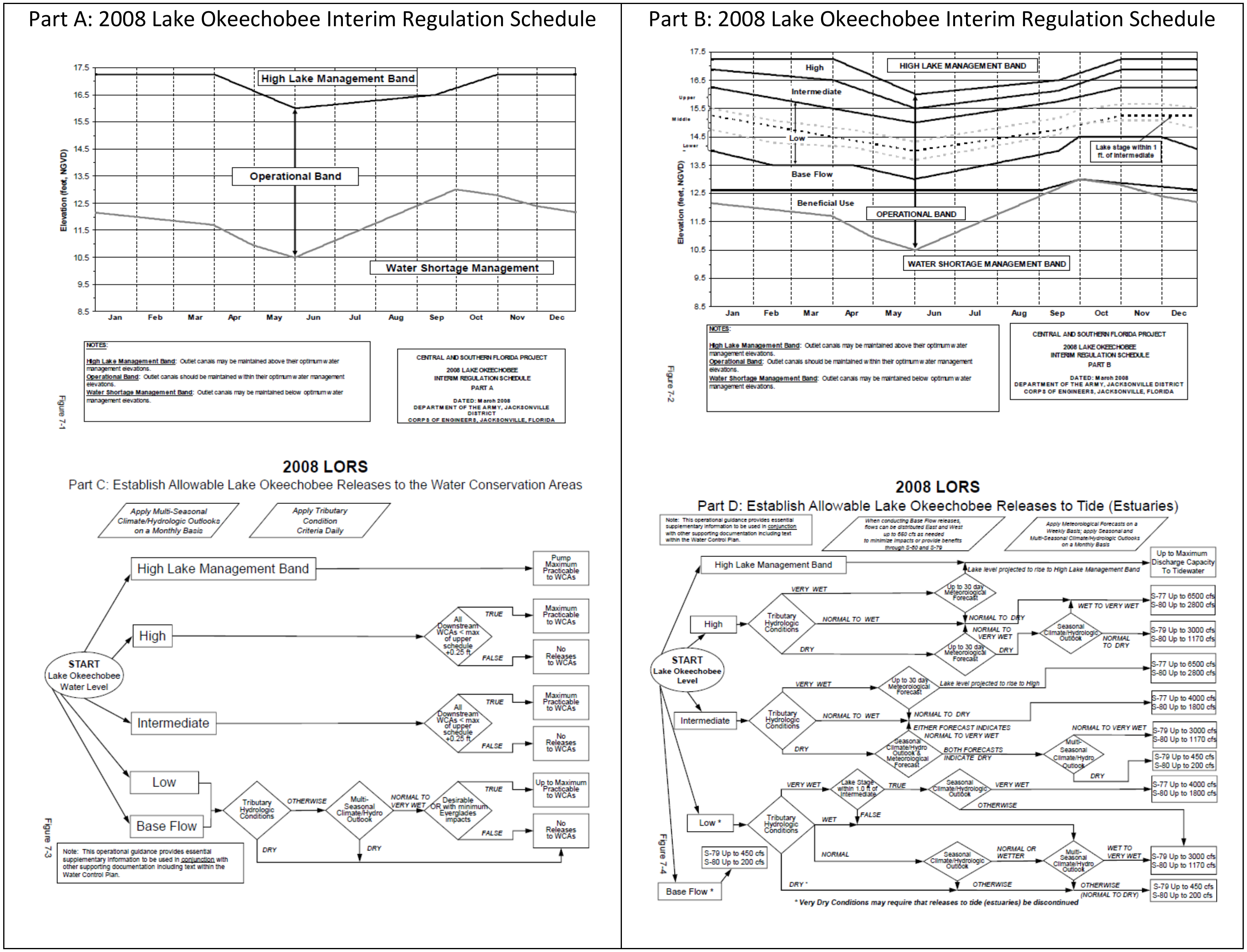


Figure IV-2. Parts A through D of LORS2008.

On a monthly basis, SFWMD also conducts a modeling exercise known as Position Analysis (PA) that provides a "probabilistic" outlook of Lake Okeechobee level using historical hydrology as a guide. For the PA, SFWMD's regional hydrologic simulation model, SFWMM, is used for simulating the future potential water levels for the ensuing 12-months, using historical climate data sequences as input. This exercise is different from a typical planning simulation that is continuous over several decades, as it initializes the system using the prevailing conditions for that month. However, this approach also assumes that the hydrological, climatological and weather conditions will be the same in future decades as they were in the 1965-2000 historical data. The PA produces useful information for decision-making, as it provides future conditions with respect to management objectives under a variety of hydrologic conditions. For instance, if the Seasonal or Multi-Seasonal Outlooks indicate a possible future El Niño in an Atlantic Multidecal Oscillation (AMO) Warm Scenario, water managers may pay more attention to a subsample of projected water levels corresponding to historical years that had similar conditions. Sample graphics produced by PA are shown in Figure IV-3.

Operational Flexibility in LORS2008

At the time it was adopted, LORS2008 was considered to be the "best operational compromise" for maintaining the environmental health of the major components of the greater Everglades ecosystems, while addressing the safety of the Herbert Hoover Dike (HHD), and other objectives such as water supply. Balancing the objectives of Lake Okeechobee management through the use of performance metrics associated with them, although somewhat subjective, has been a key approach used for the planning phase of the regulation schedules (Trimble and Marban 1988).

LORS2008 attempted to balance the performance of a selection of multiple objectives as assessed over the hydrology for the interval 1965-2000, but this does not guarantee that such a "balance" will be achieved in the future if the climate and hydrology regime is different from that of the historical period. The release guidance flowcharts (Parts C and D in Figure IV-2) specify "maximum practicable releases" from Lake Okeechobee, and the modeling conducted for the Planning phase of LORS2008 assumed that maximum practicable releases always occurred. In reality, however, the operational decision-making process to determine actual releases considers a variety of additional factors, including current estuary conditions, local runoff and downstream impacts (EIS, page 91). This departure from planning-model assumptions is incorporated in the Operational phase of LORS2008 in the form of real-time "operational flexibility" to address conditions (e.g., hydrology, estuaries, local runoff) that were not in the period of record. This flexibility allows water managers to alter releases to fit prevailing conditions. According to the Final Supplemental EIS (2007), examples of conditions that may require implementation of Operational Flexibility include, but are not limited to: (a) undesirable/prolonged high lake levels;

(b) climate conditions (e.g., El Niño, hurricanes); and (b) opportunities for low-volume releases to prevent high lake levels and algal blooms, and to manage saltwater intrusion.

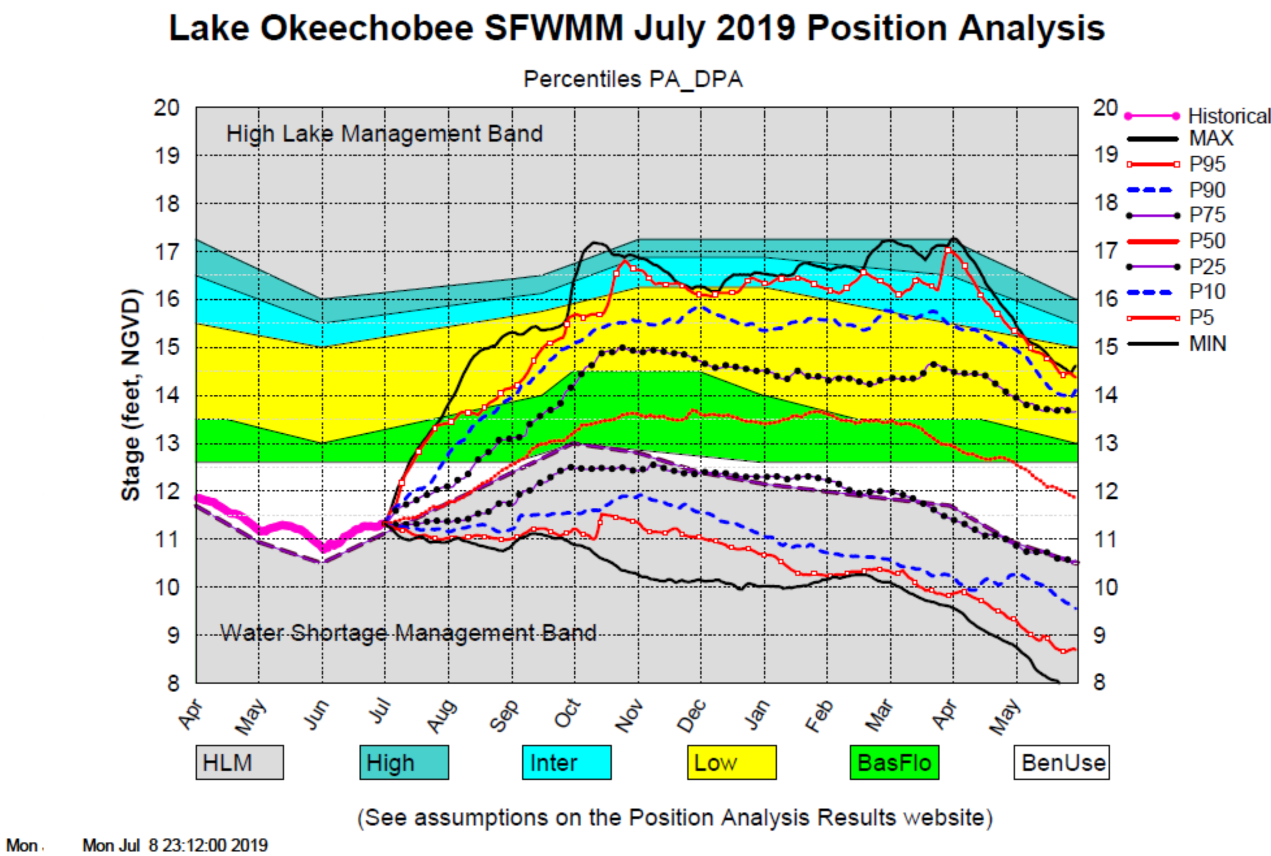


Figure IV-3. Lake Okeechobee water level percentiles for the 12-month period beginning July 2019 as simulated by the PA using SFWMM.

Depending on the frequency of use of "operational flexibility," the outcomes of lake management decisions may deviate from the outcomes of the planning exercise used to select a schedule that was deemed to be the "best operational compromise." As a result, future lake levels may deviate significantly from the levels that would have resulted if the rules of operation developed during the planning phase were followed. Figure IV-4 (SFWMD, 2019) demonstrates consequences of such a departure. This graphic shows historic lake levels (black trace) and the simulated lake levels that would have occurred had maximum estuary releases used during the planning phase of LORS08 for the period 2014-2015, been implemented. The table in the figure shows a comparison of release volumes to various downstream water bodies. Clearly, the historical lake levels are about a foot higher than the simulated stages, presumably because operational flexibility was exercised during this period. This graphic is shown, not to criticize the particular operational strategy that was used, but rather to point out the differences in outcome that could result when there are departures from the operational rules used for planning**.** The exact magnitude of the impact of the frequent use of operational flexibility is unknown, thus a retrospective assessment of historical versus simulated lake levels, for the entire period since LORS08 was implemented, is warranted. If such departures are determined to be significant, an algorithm to simulate operational flexibility should be developed and used in LOSOM Planning models to evaluate whether incorporating this flexibility negates differences among alternative regulation schedule options.

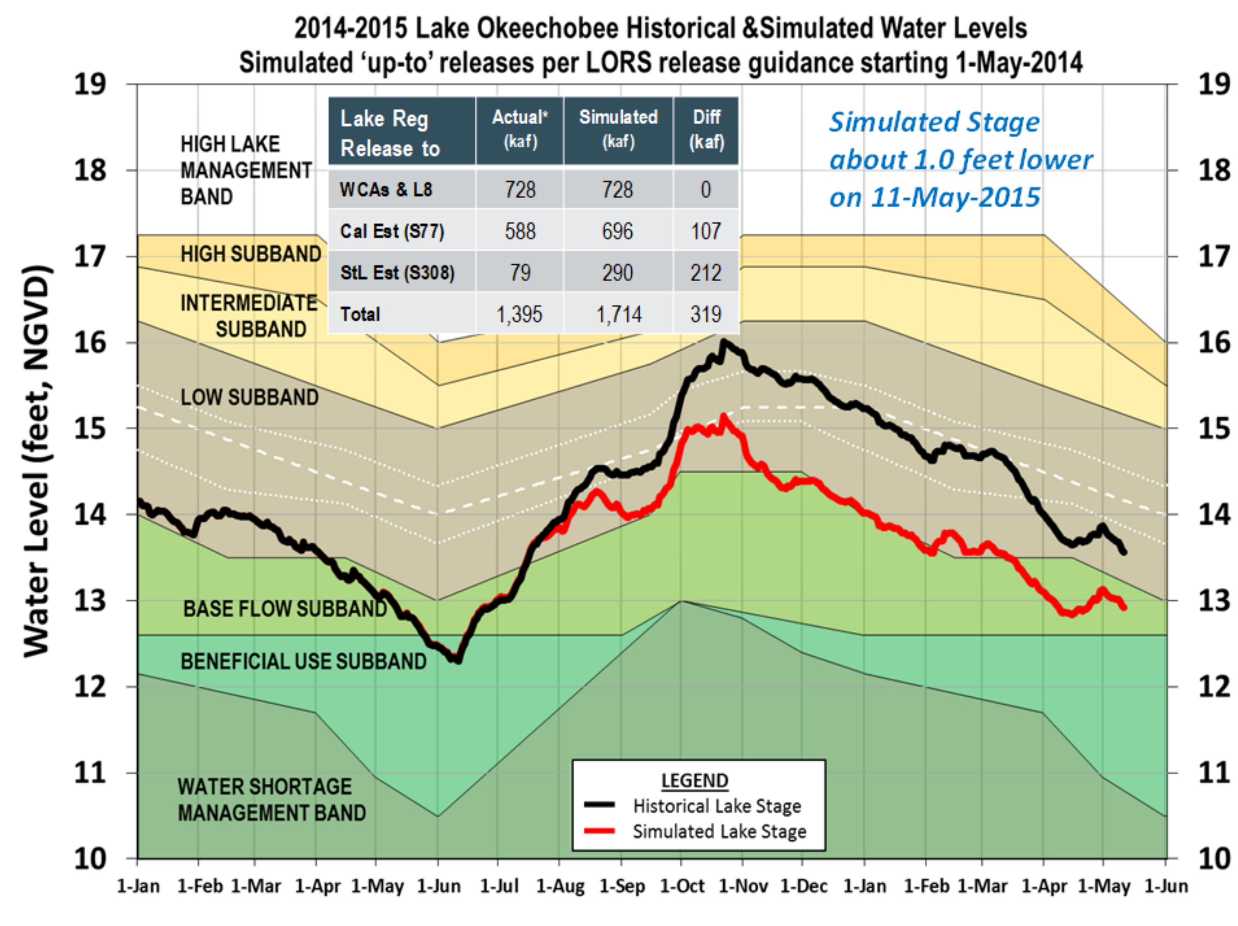


Figure IV-4. Comparison of historical and simulated lake levels and discharges for the 2014-2015 period demonstrating the potential effect of using operational flexibility to deviate from planning assumptions (source: SFWMD 2019).

Period of Climate Record for Previous Lake Okeechobee Regulation Schedules

Trimble and Marban (1988) provided a summary of the evolution of the Regulation Schedules since the mid-1950s. Previous raising or lowering of the Lake Okeechobee regulation schedule appears to have occurred after a major hydrologic event, such as an extended wet or dry period of many years. More recently, however, the structural integrity of the Herbert Hoover Dike (HHD) prompted a change to lower the lake levels, and the result was the LORS2008 schedule, which replaced the previous WSE schedule. Increasingly complex modeling tools and performance metrics, optimization methods, and historical records have been used over the last 40 years. Table IV-2 provides a summary of the multiple regulation schedules adopted since 1978.

Table IV-2. History of Lake Regulation Schedules (adapted from Neidrauer and Cadavid 2018)

LORS Name	Modeling Tool	Period of Simulation	Remarks
1978 LORS	Unknown	Likely 1965-1974	● Raised regulation range to 15.5 – 17.5 ft. NGVD. Zone A raised to 18.5
1994 LORS (Run25)	South Florida Regional Routing Model	1952 - 1984	● Added more zones ● Introduced pulse release concept
2000 LORS (WSE)	South Florida Water Management Model	1965-1995	● Better balance of water supply, in-lake and estuary performance, flood protection
2008 LORS (LORS2008)	South Florida Water Management Model/LOOPS	1965-2000	● Lowered upper bound from 18.5 ft to 17.25 ft to lower HHD risk ● Added Baseflow Sub-band to allow smaller regulatory discharges at lower stages to reduce estuary high discharge events ● Continued use of climate/hydrologic outlooks with release guidance flowcharts ● Added broad operational flexibility to federal water control plan

Since the early 1990s, the planning studies for regulation schedule development have relied on substantial modeling efforts. For the 1994 LORS, a more simplified lumped model known as the South Florida Regional Routing Model was used. Interestingly, the period of simulation for that modeling effort covered the early years of the 1950s. That likely enabled evaluation of the performance of the system during the wetter years of the 1950s and 1960s. Development of the 2000 LORS (WSE) schedule used a more complex, distributed model, SFWMM, covering the entire regional system, including the Everglades and the urbanized areas of Southeast Florida.

Hydrologic data used for that modeling, however, started only in 1965 and extended to 1995, likely a consequence of limited availability of spatio-temporal data required for the SFWMM. For the 2008 LORS (LORS2008), the same model, namely SFWMM, was used, but the period of simulation was extended to 2000 to capture five additional years of hydrology. For the next LOSOM the period of simulation is expected to be extended to 1965-2016.

The period of simulation used for modeling is important because the evaluation of multiple objectives and the selection of a schedule depend on performance metrics that resulted from the weather and hydrology that occurred during that period. Because of multi-decadal variability of Lake Okeechobee inflows, it is important to ensure that the period of simulation contains the widest possible range of inflow variability and time scales (sub-decadal to multi-decadal).

Role of Teleconnections in LORS2008 Planning and Operations

The association of a hydrologic variable to climate variables at distant locations is known as a teleconnection, a component of natural climate variability. Depending on the temporal scale of teleconnections and their predictability, they can be useful for water management. In the case of Lake Okeechobee inflows, such teleconnections have been associated commonly with phases of ENSO, AMO, and Pacific Decadal Oscillation (PDO) (Enfield et al. 2001; Obeysekera et al. 2007). The warm phase of ENSO, known as El Niño (Figure IV-5(a)), shifts the tropical Pacific rainfall moisture eastward, where the subtropical jet stream picks up and conveys the moisture to the southeastern United States. This additional moisture increases the probability of greater than normal rainfall in Florida. The El Niño teleconnection is most pronounced during winter, i.e., the dry season in South Florida. During the cold phase of ENSO (i.e., La Niña), there is an increased likelihood of below normal rainfall during the same season. As shown in Figure IV-5(b), the Dry Season (Nov-May) Net Inflow to Lake Okeechobee shows a significant relationship with the Oceanic Niño Index (ONI), representing the ENSO phenomenon. When the ONI is below -0.5, Dry Season inflows to Lake Okeechobee are significantly below normal. The ENSO cycle has an approximate periodicity of 3-7 years.

The AMO phases (cold and warm) typically have longer durations (Figure IV-6a). The AMO is driven primarily by variations in strength of global thermohaline circulation and causes decadal fluctuations in hurricane activity. During the warm phase of the AMO, there is greater probability of above normal rainfall, and therefore larger inflows to Lake Okeechobee (Figure IV-6b). Within each phase of the AMO, weather patterns in individual years may be further modulated by other teleconnections such as ENSO and PDO. The approximate periodicity of AMO cycles is of the order of several decades.

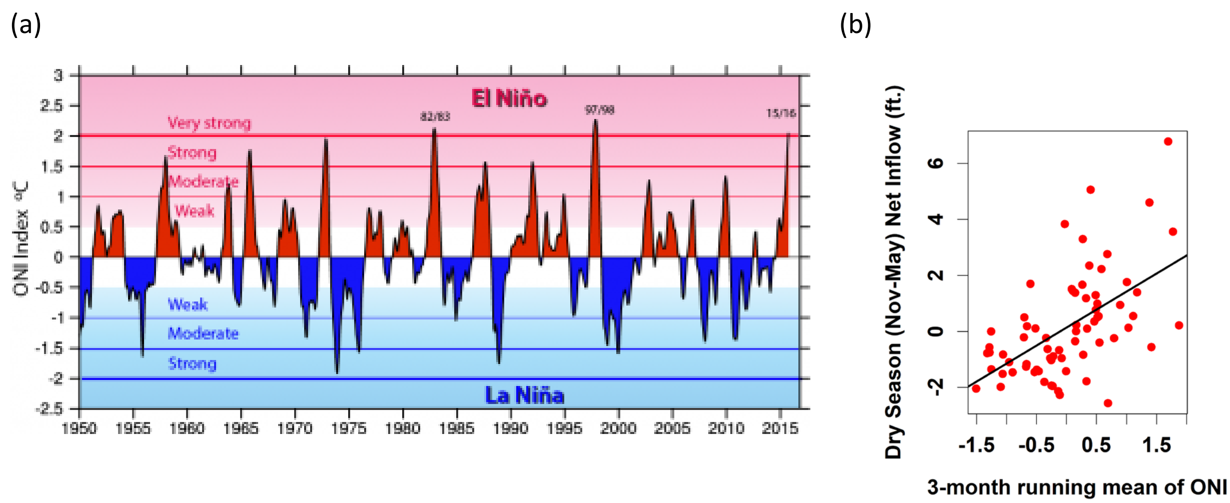


Figure IV-5. (a) The Oceanic Niño Index (ONI) shows warm (red) and cold (blue) phases of abnormal sea surface temperatures in the tropical Pacific Ocean (contributed by K. Trenberth) ENSO (Trenberth, K. & National Center for Atmospheric Research Staff (Eds.). Last modified 11 Jan 2019. **"The Climate Data Guide: Niño SST Indices (Niño 1+2, 3, 3.4, 4; ONI and TNI)."** Retrieved from https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni. (b) Dry Season (Nov-May) Lake Okeechobee Net Inflow (ft) versus 3-month average of ONI.

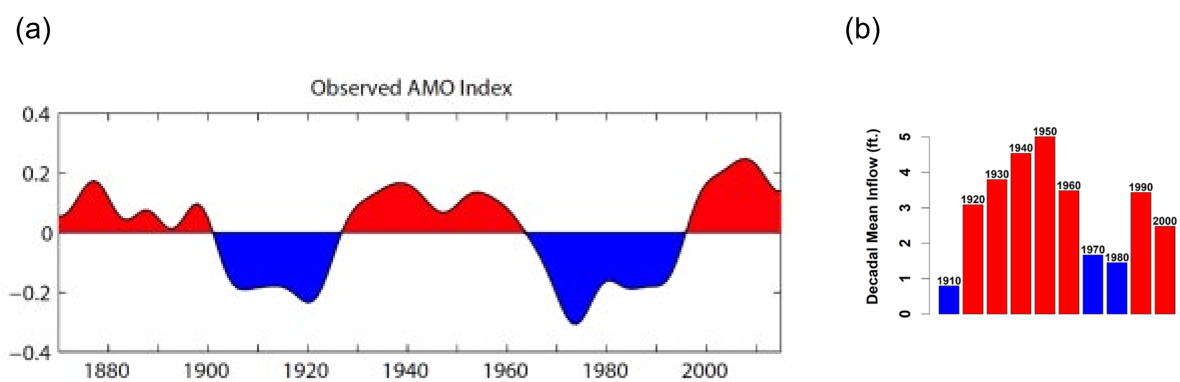


Figure IV-6. (a) AMO index (https://climatedataguide.ucar.edu/climate-data/atlantic-multi-decadal-oscillation-amo). Trenberth, K. and Zhang, R. & National Center for Atmospheric Research Staff (Eds). Last modified 10 Jan 2019. **"The Climate Data Guide: Atlantic Multi-decadal Oscillation (AMO)."** Retrieved from https://climatedataguide.ucar.edu/climate-data/atlantic-multi-decadal-oscillation-amo. (b) Decadal averages of Lake Okeechobee Net Inflow (LONIN).

Teleconnections to climate phenomena such as the AMO and ENSO are used in both planning and operational phases of the schedule development. Available daily data for estimated Lake Okeechobee Net Inflow (LONIN) from 1914 onwards, aggregated to monthly time steps, are the basis for computing both seasonal and multi-season climate outlooks. For computing these outlooks, sub-sampling from historical LONIN data is determined according to the prevailing state of the climate indicators. As an example, for El Niño, the months corresponding to the ENSO indicator > 0.4 are used, and other months are not included in the computation of the outlook. In this way, the expected LONIN outlook under particular states of climate indicators, is used as a factor in making a release decision.

Teleconnections are extremely useful for development of regulation schedules that consider climate outlooks, as demonstrated in Parts C & D of LORS2008 (Figure IV-2). However, the longer recurrent period ("periodicity") of AMO leads to some challenges in the planning phase of schedule development. It is impossible to predict exactly when there will be a switch from one phase of the AMO to another (e.g., warm to cold). Because each phase can be decades long, with potential differences in inflows to Lake Okeechobee, it is challenging to base the performance of a particular schedule solely on the historical period, which may contain only one or two AMO cycles. For the several decades following the implementation of a schedule, what matters is AMO phases and when they switch from one to another. It is therefore important to consider the characteristics of the historical period used for planning, to ensure that sufficient intervals of wetter and drier decades, and consequent different inflow regimes, are present in the data.

Climate Variability in LORS2008 Planning Period of Simulation

For LORS2008, SFWMD's regional-scale hydrologic simulation model, the SFWMM was used. SFWMM requires extensive hydrologic data as input, but at the time of the planning phase for the LORS2008, only data for 1965-2000 were available. A large portion of this simulation period was in the cold phase of the AMO (Figure IV-6a) and included extended dry years in the early to mid-1970s. That period did not include high-frequency hurricane activity that is typical of the warm phase of the AMO, as was observed in the late 1940s and the 1950s. During this period of several wet years, large inflows led to Lake Okeechobee stage rises of more than 6 feet (1.8 m) during the wet season months of June through October (Figure IV-7). The period of simulation also did not include similar high, wet season inflows that occurred in 2004 and 2005, which also included multiple land-fall hurricanes. Visual observation of the wet season Lake Okeechobee Net Inflow (LONIN) also shows (Figure IV-7) increased frequency of low inflows (near or below zero feet of LONIN) during the simulation period. Because the simulation period used for LORS2008 did not include frequent tropical storms/hurricanes and had a higher frequency of low to very low inflows to Lake Okeechobee, the preferred alternative, derived by balancing flood protection and water supply, may not be ideal for a climate regime that includes more hurricanes and fewer droughts. The Final EIS of the LORS2008 reports the use of the simplified spreadsheet model known as the Lake Okeechobee Operations Screening (LOOPS) Model, for evaluating the selected alternative for the extended period 2001 to 2005. This analysis indicated that the selected alternative was “deemed effective” for managing high lake elevations under the hydrology of this period (page 90, Final SEIS). A brief summary of LOOP’s output was included to justify this conclusion (Page E-45, Final SEIS).

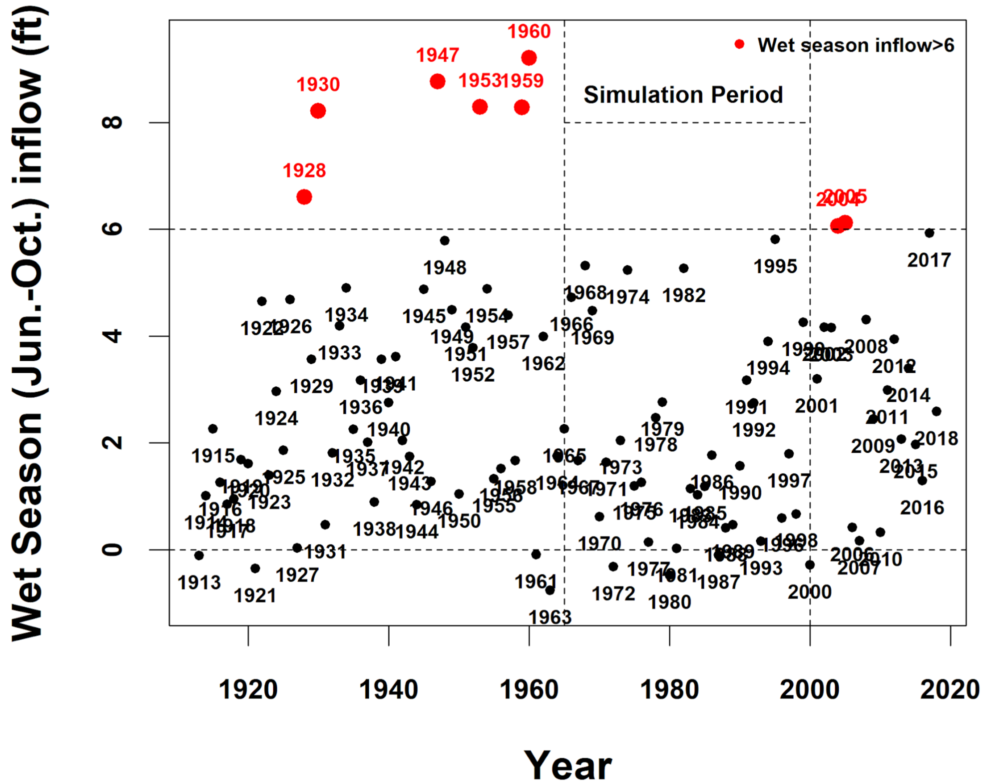


Figure IV-7. Wet Season Lake Okeechobee Net Inflow (LONIN, expressed as feet over Lake Okeechobee) for the historical period. Also shown is the Period of Simulation used for SFWMM modeling associated with LORS2008. Points in Red show the years with LONIN > 6 feet.

Climate Variability in Actual LORS2008 Operations

Figure IV-8 presents the outflows from Lake Okeechobee to the Caloosahatchee River via the S77 spillway and the lake levels from 1965 to 2019. The simulation period used for the development of LORS2008 (i.e., 1965-2000) is also identified in this figure. Lake levels were higher during the early to mid-2000s, but have been consistently lower since about 2008. This result is consistent with the goals of the LORS2008, i.e., lowering lake level to protect the HHD. However, the discharge time series at S77 shows that increased discharges to the Caloosahatchee River (primarily in the range of 500-2000 cfs) have been necessary to achieve this goal. The wetter period of the 2000s, exemplified by a couple of major hurricanes, also likely contributed increased releases to the Caloosahatchee. Similar increases to St. Lucie were likely but were not inspected for this analysis.

As discussed, the planning simulation period was dominated by the AMO Cold Cycle, and as a consequence, there were fewer hurricanes and wet years, thus requiring lower discharges, in the range 500-2000 cfs (Figures IV-7 and IV-8). It is likely that because the LORS2008 planning period consisted of lower inflows, along with the fact that lower high Lake Okeechobee levels were maintained to protect the integrity of the HHD, consequent smaller lake storage would have resulted in reduced water supply during the dry season of the drier years in the planning period. The possibility of future wet years, with higher frequencies of hurricanes (such as occurred in the late 1940s, 1950s and 2000s) should be considered in the development of the next LOSOM.

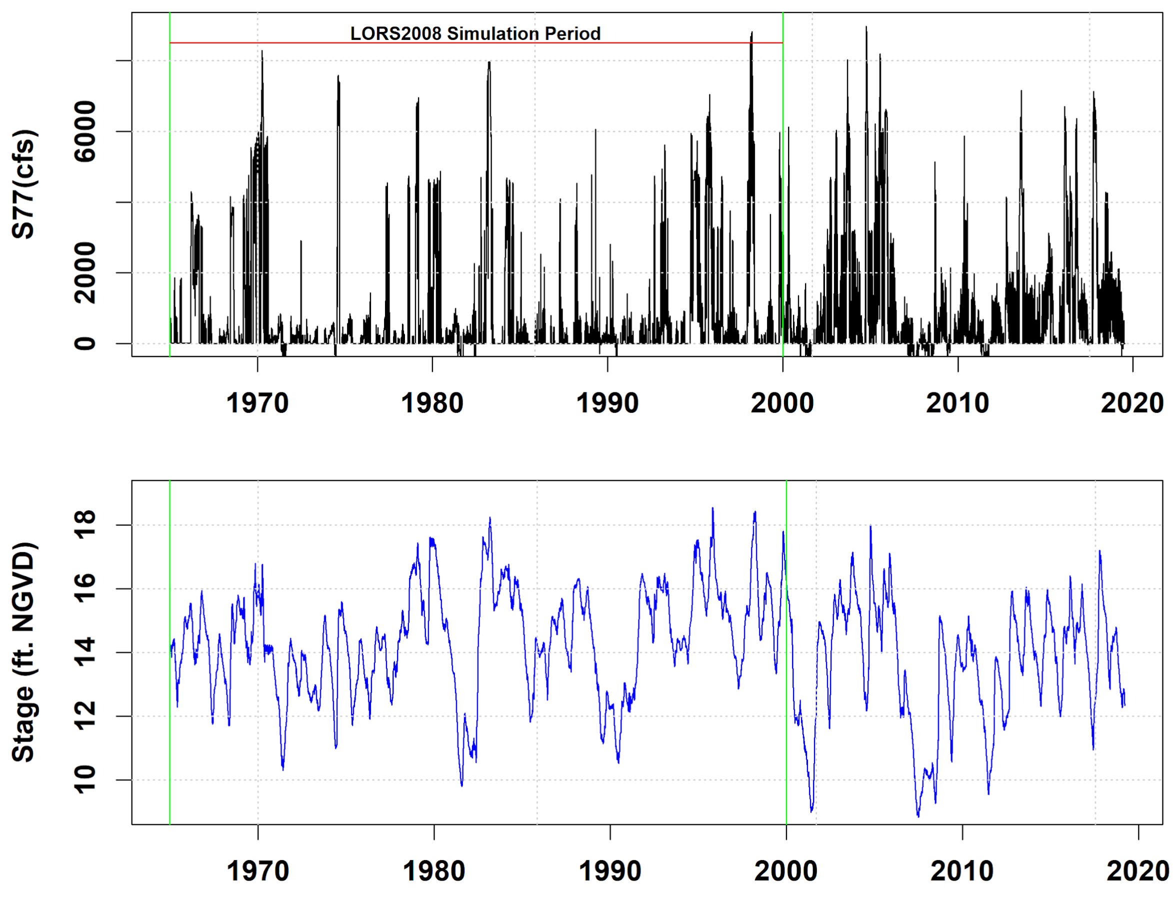


Figure IV-8. Historical S-77 discharges and Lake Okeechobee Stage.

In summary, the period of record used to develop LORS2008 spanned many years of the AMO cold cycle and did not represent multi-decadal AMO warm cycles, characterized by greater frequency of hurricanes that produce large inflows. Occurrence of wetter periods that were not representative of the period of planning simulation, may result in frequent use of the operational flexibility and departures to address unusual hydrologic conditions that were not used for schedule development**.** The climate data used in the next LOSOM planning models should be expanded to include more AMO/ENSO variability, hurricanes, droughts and other extreme events. This could be accomplished by using information from long-term (~1915-present) historical weather data or by generating synthetic realizations representative of historic data (Rajagopalan and Lall 1999; Kwon et al. 2009; Doss-Gollin et al. 2019). At a minimum, the next LOSOM planning effort should verify that the extended hydrologic inputs currently planned for use (1965-2016) include wet periods representative of the entire historical record, particularly those outside the LORS2008 simulation period. Including the wet periods of the 1950s and 2000s is especially important.

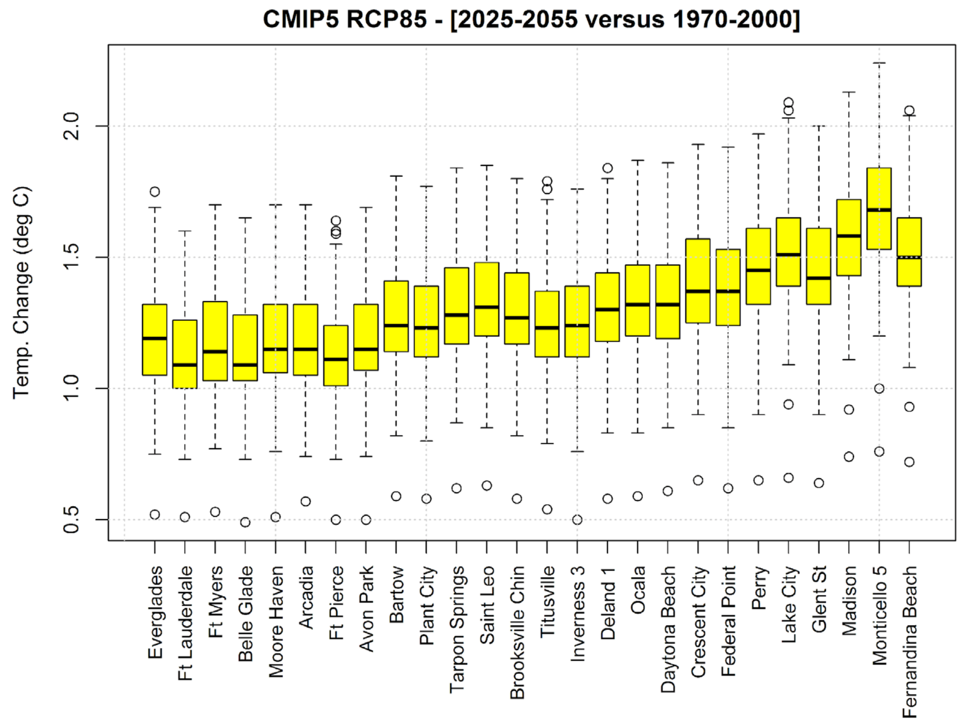
Climate Change Considerations for the Next LOSOM

Climate can be highly variable because of natural phenomena, including teleconnections. Recent awareness of the implications of increased Green House Gases (GHGs) has prompted concerns that the climate is also exhibiting systematic, nonstationary trends. The premise of using historical hydrology to develop a future regulation schedule is questionable, particularly if the climate regime for the planning horizon is very different from that of the historical period. Inflows to Lake Okeechobee are influenced not only by rainfall patterns, but also by temperature and other meteorological variables, which influence water losses in the tributary basins through evapotranspiration. Additionally, the salinities of the receiving estuaries will be determined by Lake Okeechobee releases of fresh water and how that mixes with seawater; as sea levels increase, more saltwater will be entering the estuaries. If climate in the region is changing, it is necessary to determine its impact on regulation schedule development. The next regulation schedule (LOSOM) is expected to be implemented after repairs to the HHD are completed (scheduled for 2022) and will likely be in place until the CEPP and associated EAA reservoir are completed, unlikely until after 2035. Consequently, the new schedule is likely to be in place for 10-15 years. The question is, “what can we expect over the next few decades?”

The current state-of-the art does not enable accurate forecasts of climate over periods of several years to decades. Thus, although changes in climate teleconnections such as AMO may influence the climate in the tributary basins over a period of one to two decades, it is not possible to predict the exact timing of the switching from one mode to another. Nevertheless, many attempts to investigate longer-term future climate projections in South Florida have evaluated output from available climate models, at both global and regional scales, produced via downscaling (Obeysekera et al. 2011; Obeysekera et al. 2015; NRC 2014, 2018).

A recent assessment of the CMIP5 climate projections (Obeysekera et al. 2014; Dessalegne et al. 2016) for the near-term period (2025-2055) shows a unique spatial pattern in the state of Florida (Figure IV-9). Both temperature and precipitation projections increase from south to north. Median changes in temperature and precipitation in locations north of Lake Okeechobee are approximately 1.2-1.5 °C, and about 5%, respectively, whereas for locations south of Lake Okeechobee the changes are lower, closer to 1.0 °C and 3%, respectively. Model output also shows a possible change in the seasonality of rainfall patterns (Figure IV-10). Since the magnitude of change is significant for some model projections, it is important to develop hydrologic scenarios that reflect such a change in climate for the development of the next regulation schedule, which will likely be operational into the mid-2030s or beyond.

The SFWMM requires a continuous time series of LONIN for modeling at a daily time step. One option to develop representative time series is to use the best available climate model output to drive a hydrology model to simulate future realization of LONIN. Recently, SFWMD embarked on such an exercise using the downscaled climate data published by the US Bureau of Reclamation for the CMIP5 suite, and the algorithms of the MCRAM model developed by the USACE for the Lake Okeechobee Risk Management Study (Irizarry 2017). This effort produced inflow time series from 119 climate models and is an excellent starting point for the development of future potential LONIN time series for use in the next LOSOM. The LOCA climate model data set (http://loca.ucsd.edu/, Irizarry et al. 2018), published by USBR, is likely the best downscaled climate data available for South Florida. This data set is recommended for use in future LOSOM efforts unless it can be demonstrated that subsets of the observed 1965-2016 climate record, currently planned for use in the next LOSOM, have the ability to represent the range of future climate variability contained within the downscaled datasets. If this is found to be the case, the output from such periods could be used as surrogates for investigating climate change implications.



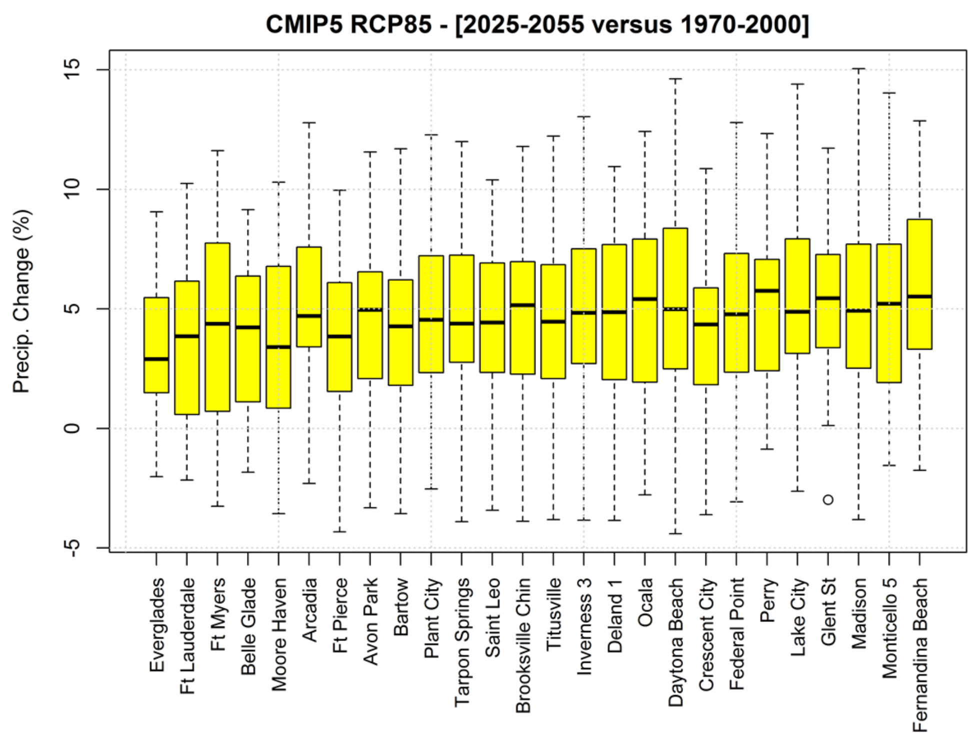


Figure IV-9. Spatial pattern of (a) temperature and (b) precipitation projections for 2025-2055 as determined from downscaled CMIP5 model results.

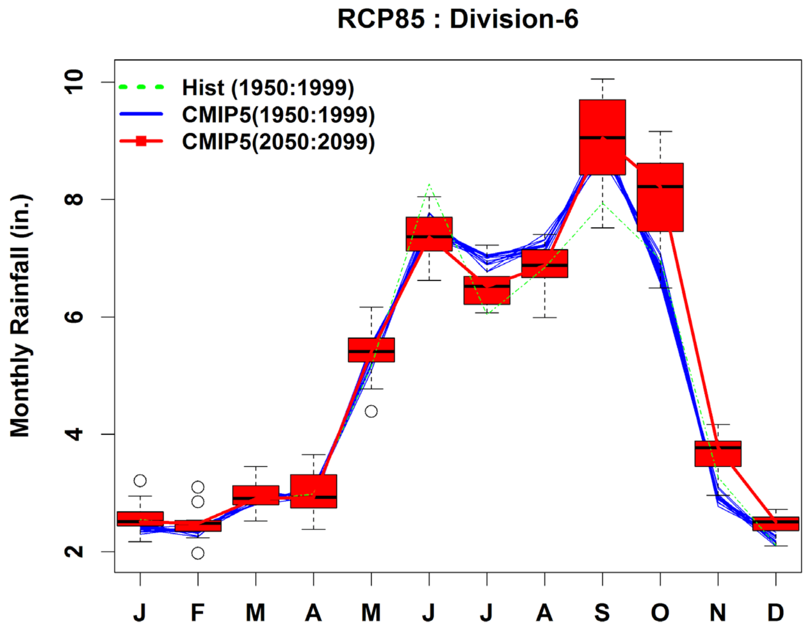


Figure IV-10. Seasonality change in future rainfall showing lesser rainfall during summer months and higher rainfall in the early dry season.

Sea Level Rise Considerations for the Next LOSOM

Sea level is rising along Florida's coastlines. Tide gage records show that the sea level is rising at a rate of about 3 mm/year (0.12 in) in South Florida. Figure IV-11 shows the historical sea level at tide gages in Fort Myers, Lake Worth Pier, and at Key West, with rising trends of 3.1 mm/yr (0.12 in/yr), 3.5 mm/yr (0.14 in/yr), and 2.4 mm/yr (0.10 in/yr) , respectively. All aspects of water management, including flood protection, water supply, and environmental protection and restoration, will be influenced by rising sea levels (Obeysekera et al. 2011). The impacts will include, but are not limited to, increased flooding and inundation, saltwater intrusion along rivers and canals with open connection to the ocean, and saltwater intrusion into freshwater aquifers. Potential effects of rising sea levels on Lake Okeechobee operations associated with both the Caloosahatchee and St. Lucie Estuaries, and along the southeast coast, are described below.

Operation of water control structures S-79 and S-80, which discharge Lake Okeechobee regulatory releases to the Gulf of Mexico and Atlantic Ocean, respectively, will likely be influenced by future sea level, depending on the magnitude of the rise. Sea Level Rise projections from the US Army Corps of Engineers at Fort Myers are used to illustrate potential effects of rising sea levels in the Caloosahatchee Estuary and operation of the S-79 structure (also known as the Franklin Lock and Dam), for both flood protection and water supply. Using the Sea Level Rise

Calculator provided by USACE, Low, Intermediate, and High curves of future sea level rise were computed, as shown in Figure IV-11. Also shown in this figure are the mean annual sea level, and the 19-year moving average of the annual mean sea level (MSL). The 19-year cycle approximates the lunar nodal cycle and removes its effect on the mean sea level datum. Observations in Figure IV-12 demonstrate the increasing sea level trend at the Fort Myers tide gage. The data since 1992 (current tidal epoch) appear to follow a trend above the Intermediate curve. Since 2012, six out of about eight annual MSL values track the High curve. This trend has been observed in other tide gages around South Florida (data not shown, https://climate.sec.usace.army.mil/slr_app/). Consequently, for planning purposes it is prudent to assume that mean sea level by 2035 corresponds to the High curve, which is approximately 0.2 m (0.66 ft) above NAVD. Since the 1992 MSL datum is -0.125 m (-0.41 ft), the 2035 estimate of MSL represents an increase of 0.325 m (1.07 ft) above MSL for 1992. It should be noted that as mean sea level increases, extreme sea levels will also increase.

The rising sea level described above has the potential to affect discharge capacity of the S-79 structure. According to the structure information manual, available from SFWMD, under the design conditions, the capacity of this structure is about 29,000 cfs, with headwater and tailwater (tidal) elevations of 4.4 ft. NGVD29 and 3.9 ft. NGVD29, respectively. This is a mere 0.5 ft (approximately 0.15 m) elevation difference under design conditions. If there is a desire to maintain the headwater at design levels, rising sea levels may reduce the discharge capacity at the structure, potentially affecting flood protection upstream. Thus, there may not be sufficient storage capacity in the basin to retain flood waters during high tides and storm conditions. With rising sea levels, it may not be possible to discharge regulatory releases from Lake Okeechobee via S-77 at the same discharge rates that are possible today. With higher sea levels, ocean water may also overtop the closed gates at S-79, which are at an elevation 4.2 ft. NGVD.

Similar flooding concerns exist in communities along the St. Lucie River, downstream of the S-80 control structure. Rising sea levels will increase both the tides and storm surge, which may increase flooding of these communities. During times of high tide and storms, it may not be advisable to make large regulatory releases via the S-80 structure, as that may exacerbate flooding. It is clear that the LOSOM planning studies should include an assessment of potential flooding in communities along both the Caloosahatchee and St. Lucie Rivers and Estuaries, and perhaps incorporate adaptation strategies to deal with the potential limitations of water control structures that discharge flood waters to the two estuaries.

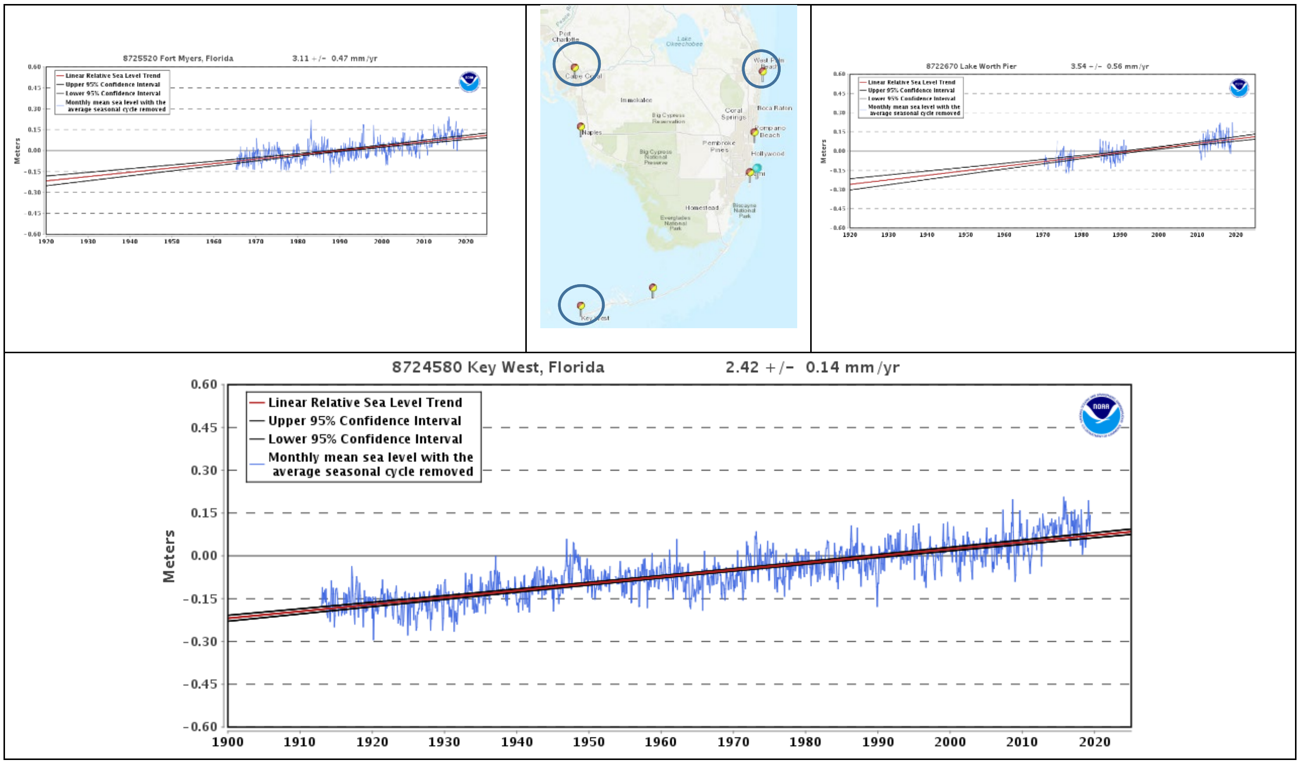


Figure IV-11. Sea level trends at tide gages in Fort Myers (upper left), Lake Worth (upper right), and Key West (bottom).

Rising sea levels will also move the surface water saltwater front inland via rivers and canals linked to the ocean, and this may negatively affect water quality and environmental health in portions of the estuaries. In the case of the Caloosahatchee Estuary, increasing salinity inland may result in an increase in exceedances and violations of the Minimum Flow and Level (MFL) criteria during drier periods. The new MFL criteria require delivery of a 30-day average flow of 457 cfs at S-79, At present, the revised MFL criteria for the Caloosahatchee Estuary are not met (SFWMD 2018). In response to comments from a peer review panel assembled to review the new MFL criteria, SFWMD conducted several modeling studies to investigate salinity changes caused by sea level rise. They found that the salinity change was insignificant for an increase in sea level of about 2 in (0.05 m), but with a rise of about 8 in (0.2 m) peak salinity in the dry season may increase by 2-3 psu at the Ft. Myers station. As indicated above, sea level rises as great as 13 in (0.325 m) may occur by 2035.

Rising salinity is a concern for maintaining habitats for plants such as *Vallisneria,* particularly in the Caloosahatchee Estuary. Salinity is also an important consideration for the water intake at the Olga Water Treatment Plant in Ft. Myers Florida. Occasionally, water managers make dry season releases from Lake Okeechobee to manage salinity at this intake, particularly during droughts.

Because of rising sea level and the resulting increase in saltwater intrusion, there may be a significant increase in the frequency of higher salinity levels at the intake and more water may have to be released from Lake Okeechobee during dry periods. Another area of concern is saltwater intrusion into the Biscayne Aquifer in the urbanized areas of the Lower East Coast and the Coastal Everglades (Dessu et al. 2018). Management of the saltwater front during dry periods in this region is accomplished by maintaining canals with water released from Lake Okeechobee. For the aforementioned reasons, dependency on Lake Okeechobee for supplemental water supply can be substantial. Rising sea levels will accelerate the migration of the saltwater front inland, potentially requiring more water from Lake Okeechobee at the same time water releases are needed to meet agricultural demands. Thus, dependency on Lake Okeechobee for water supply during the dry season and droughts, could increase as a consequence of sea level rise, and this should be considered in the planning studies for the LOSOM.

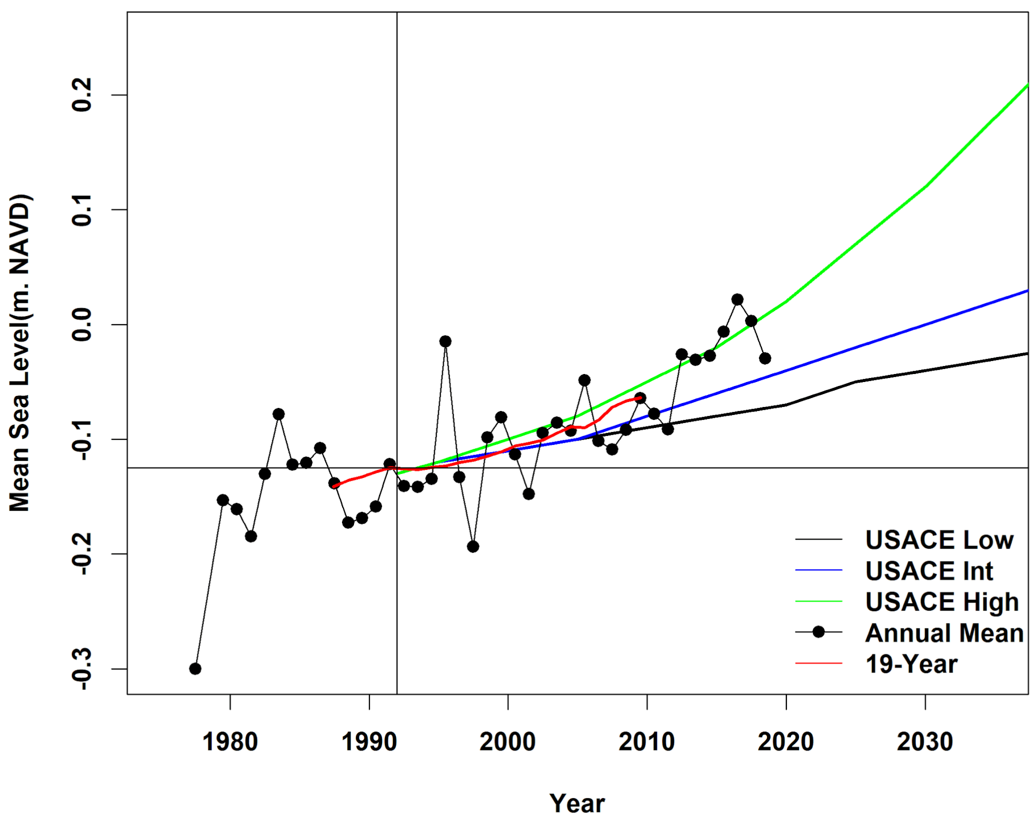


Figure IV-12. USACE sea level rise projections for the Fort Myers tide gage. Also shown are the mean annual MSL and the 19-year running mean of the annual means. Currently, no sea level rise is assumed in SFWMM simulations.

Climate Scenario Assessment

Based on a review of available information, Obeysekera et al. (2015) developed a set of future climate and sea level scenarios to assess potential impacts on the South Florida water management system (Table IV-3). The study focused on a 50-year planning horizon, roughly centered around 2060. For each scenario, changes in hydrology of the tributary basins of the system, and water demands, were estimated using approximate methods and these were used as input to the regional-scale SFWMM. The results of this sensitivity analysis demonstrated the potential impact of future climate and sea level rise on Lake Okeechobee levels (Figure IV-13) and the importance of considering potential changes in both rainfall and temperature. This scenario approach is a type of sensitivity analysis that could be incorporated into the next LOSOM.

Table IV-3. Modeling scenarios based on temperature, precipitation and sea level rise projections.

Scenario Name	Temperature Change	Precipitation Change	Sea Level Rise	Coastal Canal Levels Increased?
BASE	No change	No change	No change	No
-RF	No change	-10%	No change	No
+RF	No change	+10%	No change	No
+ET	+1.5 °C	No change	0.46 m (1.5 ft)	Yes
-RF+ET	+1.5 °C	-10%	0.46 m (1.5 ft)	Yes
-RF+ETnoC	+1.5 °C	-10%	0.46 m (1.5 ft)	No
+RF+ET	+1.5 °C	+10%	0.46 m (1.5 ft)	Yes

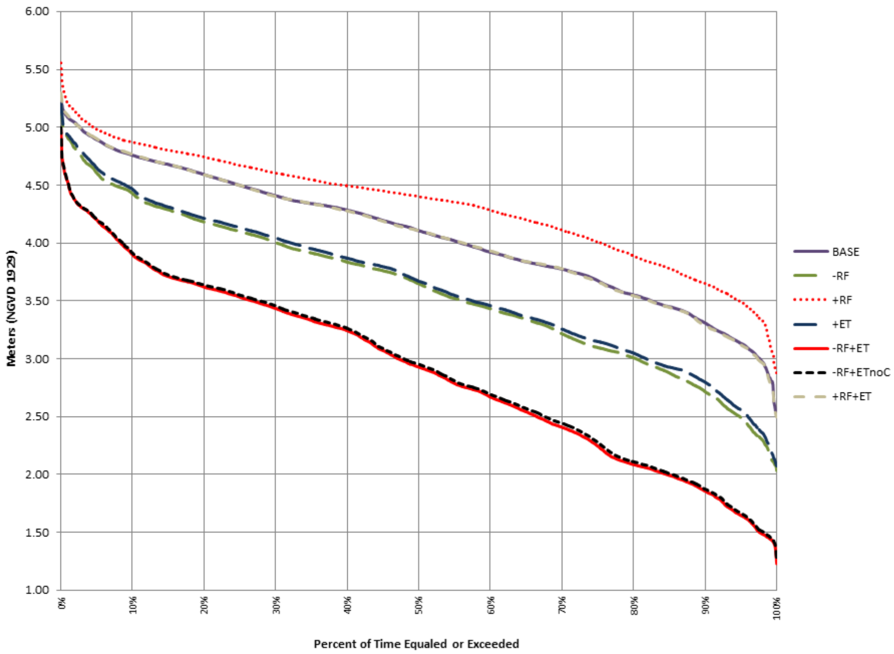


Figure IV-13. Lake Okeechobee stages for the scenarios listed in Table IV- 3.

The planning horizon for the next LOSOM is likely to be relatively short (10-15 years) compared to previous planning exercises. In the near term (up to 2035), it is unlikely that there will be a significant change in rainfall regime in the tributary watersheds because of climate change associated with greenhouse gases. Nevertheless, climate sequences available from downscaled global climate models for the retrospective and 2020-2055 periods, may be useful to supplement the variability represented in historical climate data.

In designing LOSOM, it is important to investigate consequences of possible realizations of rainfall and flow patterns over the short, 10-15-year planning horizon. A recommended approach is to evaluate the performance of alternative regulation schedules over subsets of 10-15-year climate sequences that cover wetter and drier regimes. This would ensure the Preferred Alternative is sufficiently robust to achieve the lake management objectives, to the greatest extent possible, within either of these extreme, shorter-term conditions, and could reveal vulnerabilities that could be overlooked if performance were only evaluated in aggregate over longer-term, 40-50-year conditions.

Alternative climate sequences over the short-term planning horizon could be obtained from: subsets of the historical data covering ~1915 to present; statistically generated climate sequences based on historical data (Rajagopalan and Lall 1999; Kwon et al. 2009; Doss-Gollin et al. 2019); and/or from the retrospective and near-future climate model data sets (http://loca.ucsd.edu/, Irizarry 2017, Irizarry et al. 2018). Furthermore, as shown above, projections of sea level rise are available and should also be used to develop potential conditions over the planning horizon. Performance of alternative regulation schedules over these alternative climate and sea level rise data could be evaluated using “stress test” or “scenario discovery” analysis techniques, to evaluate their robustness over a range of possible climates (e.g., Lempert 2013; Brown et al. 2011; Chang et al. 2018). The assessment of performance over shorter-term climate sequences that characterize regimes of natural variability (e.g., ENSO, AMO, hurricanes), in addition to the traditional planning approach, using the continuous simulation of the entire period of historical hydrology, would strengthen the LOSOM planning process.

Recommendations

- A retrospective assessment of actual versus simulated lake levels should be conducted for the entire time period since LORS2008 was implemented, to understand the extent to which actual operations deviated from planned and/or modeled operations because of the use of operational flexibility. If such departures are determined to have been substantial, operational flexibility within LOSOM release guidance flowcharts should be simulated in the planning process to evaluate whether incorporating this flexibility negates differences among alternative regulation schedule options considered during the planning phase.
- The climate data used in the new LOSOM planning models should be expanded to include more AMO/ENSO variability, hurricanes, droughts and other extreme events. This could be accomplished by leveraging information from long-term (~1915-present) historical weather data, by generating synthetic realizations representative of historic data, and/or by using projected future climate data for the 2025-2050 time period.
- Sea level rise scenarios corresponding to the high USACE projection for 2035 should be used in LOSOM planning to evaluate the robustness of structure operations, flood control, water supply (saltwater intrusion), and estuary salinity envelope performance measures for the proposed alternative plans.
- For each LOSOM alternative, the response of hydrologic-water quality-ecosystem performance measures to expanded climate and sea level rise data should be evaluated using climate “stress test” or “scenario discovery” analysis methods. This should include analysis of performance over the entire expanded historic climate sequence, over subsets of decadal wet or dry periods that may occur during the next LOSOM, and under projected climate change/sea level rise conditions for the 2025-2055 time period.

V. Improvements in Performance Measures, Tradeoff Evaluation and Decision Making

Performance Measures

Historically, the development of a regulation schedule has involved evaluation of several candidate alternatives that are compared using selected metrics, known as Performance Measures, which reflect the individual performance of multiple objectives affected by Lake Okeechobee operations. These objectives include flood protection, water supply, navigation and the protection and/or restoration of ecosystems throughout the Greater Everglades. Performance Measures, for the most part, have been quantified using summary statistics of hydrologic variables such as stage and discharge generated from the SFWMM period of record simulation of the various alternatives. For example, the following Hydrologic Performance Measures were used for LORS2008:

- Lake Okeechobee Ecology
  - Extreme low stage: Frequency and duration below 11 ft NGVD
  - Extreme high stage Frequency and duration above 17 ft NGVD
  - Percent of time within 12.5-15.5 ft stage envelope
  - Number of times stage >15 ft for more than 365 days
  - Number of exceedances of Lake Okeechobee Minimum Water Level and Duration exceeded (should not be below 11 ft for more than 80 days)
- Caloosahatchee Estuary Ecology
  - Counts of mean monthly flows <450 cfs, 450-2800 cfs, 2800-4500 cfs, >4500 cfs (total and total within Mar-Jun)
  - Duration of flows >4500 cfs
- St Lucie Estuary Ecology
  - Counts of mean monthly flows <350 cfs, 350-2000 cfs, 2000-3000 cfs, >3000 cfs (total and total within Mar-Jun)
  - Duration of flows >3000 cfs
- Lake Worth Lagoon Ecology
  - Counts of 7-day moving average daily flow <500 cfs, 7-day moving average daily flow >500 cfs, 2-day moving average daily flow >1000 cfs (salinity envelope protection)
- Water Conservation Area Ecology (Greater Everglades)
  - Total number weeks water table 1 ft or more below land surface (to prevent peat dry-out)
  - Total number and duration of weeks above threshold water depth (site-specific depth to prevent tree island inundation)
  - Percent of weeks in wading bird breeding season water level recession rates fall within specified range
  - % of weeks in wading bird breeding season water level reversal occurs
  - Frequency of rapid water level increases during snail kite breeding season (apple snail protection for snail kites)
- Lake Okeechobee Service Area for Water Supply

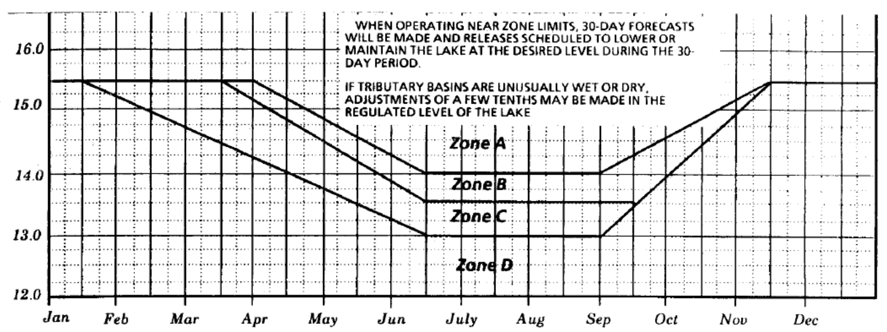
- Volume of Supply Side Management Cutbacks (acre-feet)
    - Frequency of Water Shortages (years)
    - Duration of Water Shortages (months)
    - Severity of water shortages score
    - Water years with SSM cutbacks >100,000 acre-feet
    - Water years with SSM cutbacks >200,000 acre-feet
    - EAA percent of Demands not met
    - Other LOSA percent of Demands not met
    - Coastal Basin Supply Side Management water shortages
- Herbert Hoover Dike Protection
    - Frequency and Duration above 17.25 ft
- Navigation
    - Frequency Lake Okeechobee Stage below 12.56 ft

These hydrologic surrogates, used to represent water quality, ecological and economic implications of Lake Okeechobee management throughout the South Florida Ecosystem, may not be adequate to assess accurately the consequences of water management operations, since outcomes may depend on factors other than, for instance, the number of occurrences or duration of particular stages or flows. For example, as discussed in previous chapters, the current hydrologic surrogates may not adequately take timing, duration, frequency and return interval of events, antecedent hydrologic/ecologic conditions, nutrient loads, and/or variable resilience of ecosystem components into account.

For the next LOSOM, a suite of additional Performance Measures that reflect the state of Lake Okeechobee, the Estuaries, and the Everglades, with respect to water quality and ecological conditions, should be developed. For example, current Performance Measures may not adequately represent water quality, ecological, human health and economic impacts of internal and external nutrient loadings, potential for algae bloom outbreaks, and the state of endangered species in the system. To enhance transparency when tradeoffs are made among conflicting objectives, Performance Measures should reflect issues that stakeholders and the public care about and can identify, without an in-depth scientific understanding (e.g., water clarity and an environment suitable for fish). The Technical Review Team recognizes the challenges in developing tools for producing such Performance Measures, but recommends that the agencies move beyond simplified hydrologic surrogates in a system where water quality and ecology are becoming increasingly important to the public.

The South Florida Water Management District (SFWMD) has made significant progress in developing hydrodynamic/hydrologic, water quality, and ecological models that could simulate environmental performance of alternative regulation schedules directly. The next LOSOM development could benefit significantly by using such tools in both the Planning and Operational phases. During the Planning phase, they could provide direct simulation of impacts of various proposed alternative operating schedules on both water quality and ecology. Performance Measures in Lake Okeechobee, as well as the St. Lucie and Caloosahatchee Estuaries. For real time operations, these modeling tools could provide valuable information for making release decisions. In particular, incorporation of new modeling tools may be useful to incorporate water quality and ecological antecedent conditions and forecasts into LOSOM release guidance flowcharts more quantitatively, as well as to broaden the use of Position Analysis to include outlooks of the water quality and ecological performance over ensuing seasons and beyond.

It should be noted that the explicit use of water quality concerns in the regulation schedule is not unprecedented. For instance, the Lake Okeechobee regulation schedule that was in effect in 1958 specifically recommended the consideration of the existence of "unusual Red-Tide Hazard" in the Caloosahatchee Estuary when prioritizing the use of particular Lake Okeechobee outlets (Figure V-1).



RELEASE THROUGH OUTLETS AS INDICATED

Zone	Agricultural Canals	Caloosahatchee River	St. Lucie Canal
A	MAXIMUM DISCHARGE AFTER REMOVAL OF LOCAL INFLOW	MAXIMUM DISCHARGE WITHOUT LOCAL FLOODING	MAXIMUM DISCHARGE
B	MAXIMUM GRAVITY RELEASES AFTER REMOVAL OF LOCAL INFLOW		MAXIMUM DISCHARGE WITH AVERAGE VELOCITY LIMITED TO 2.5 FT/SEC
C	MAXIMUM GRAVITY RELEASES AFTER REMOVAL OF LOCAL INFLOW	MAXIMUM CAPACITY	0 TO 3500 CFS
D	FOR AG DEMAND ONLY	NO REGULATORY DISCHARGE	NO REGULATORY DISCHARGE

PRIORITY FOR USE OF OUTLETS

1. GRAVITYRELEASES THROUGH THE AGRICULTURAL CANALS
2. ST LUCIE CANAL AND/OR CALOOSAHATCHEE RIVER DEPENDING ON LOCAL CONDITIONS. WHEN THERE IS AN UNUSUAL RED-TIDE HAZARD, RELEASES THROUGH THE CALOOSAHATCHEE MAY BE CURTAILED
3. PUMPED RELEASES THROUGH THE AGRICULTURAL CANALS

Central and Southern Florida
INTERIM REGULATION SCHEDULE--LAKE OKEECHOBEE
Department of the Army, Jacksonville District
Corps of Engineers, Jacksonville, Florida
DEC 1958

Figure V-1. Regulation Schedule that was in effect in 1958 (Trimble and Marban 1988).

Furthermore, the Regulation Schedule for the S-152 structure for the Decomp Physical Model (DPM) utilizes a decision tree that incorporates month-specific regressions to predict S-151 geometric mean Total Phosphorus (TP) concentrations one month in advance, based on previous measurements of S-151 TP concentration, L67A canal stage, and average marsh to canal stage difference (Saunders and Newman, October 2017 (Figure V-2).

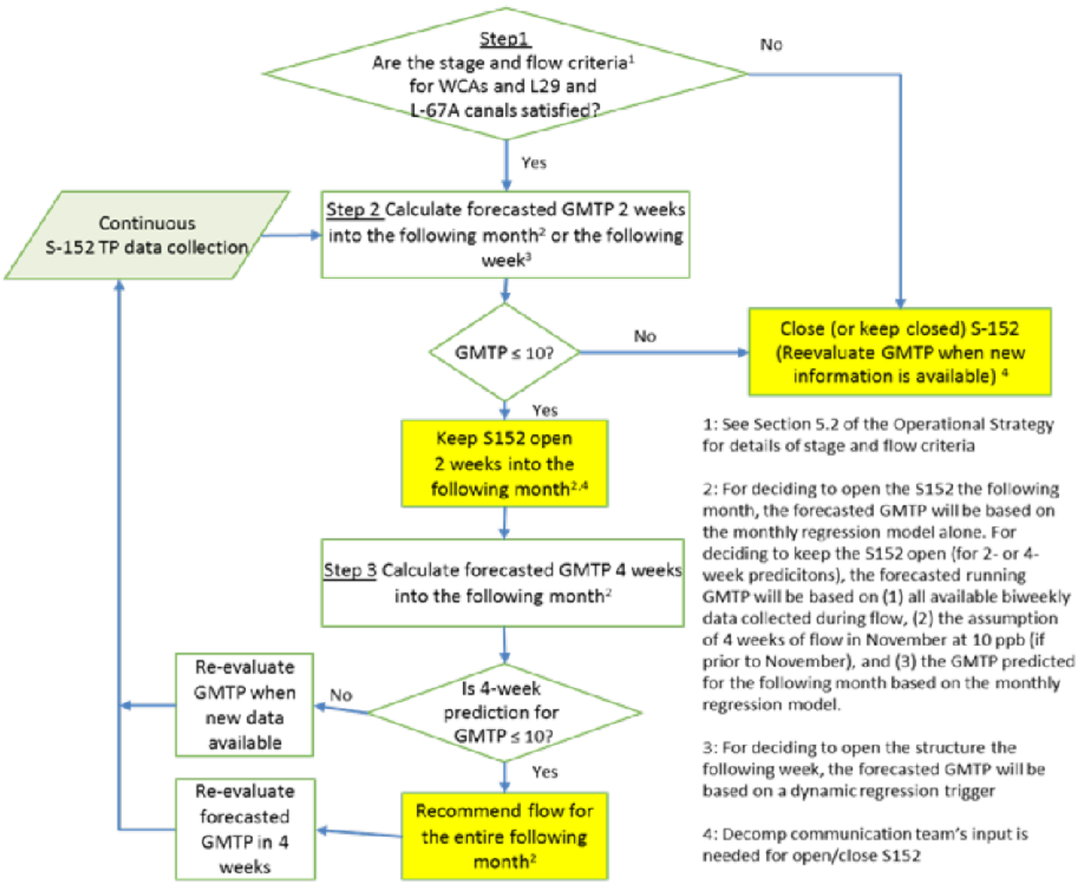


Figure 8-1. Decision tree for year-round operations of the S-152. This decision tree assumes conditions are based on previous stage and/or S-152 TP water quality data. Note that the data used to develop predictive models were from S-151, as a conservative surrogate for S-152. Trigger models used may depend on how fast operations are needed. For instance, if operations are desired within 1-2 weeks, trigger model can utilize the dynamic trigger model (based on week-to-week data, see Saunders 2015). If operations are desired for the following month, 1-month offset trigger models may be used (**Table 8-1**). 2-month offset trigger models are also being developed (see **Section 6**), but are not yet included in this application.

Figure V-2: Decision tree for year-round operations of S-152 (From Saunders and Newman 2017).

It is also not clear that current hydrologic surrogates adequately represent economic implications of agricultural and urban water supply shortages in South Florida, or the socioeconomic implications of blue-green algae blooms on tourism and real estate in the region. An economic assessment was conducted for LORS2008 (Figure V-3, reproduced from USACE 2007) that included an Economic Post Processor (EPP), using the output of the regional simulation model, SFWMM. However, it is not clear if the EPP was calibrated or validated with historic economic data. Thus, the resulting economic loss projections caused by alternative lake regulation schedules, may not be accurate enough to assess tradeoffs among disparate objectives such as agricultural water shortage, urban water shortage or disruption to navigation, commercial fishing, tourism, and real estate markets. For example, the Natural Resources Conservation Service (NRCS) reviewed 25 years of agricultural water supply data available from SFWMD, compared that information with historical data on crop yields and found that only one drought year (1982) resulted in a significant shortage of irrigation water (Page D22, USACE 2007). Historical data such as this should be compared with the agricultural water shortages produced by SFWMM to ensure that projected water shortages and estimated economic losses are realistic. Accuracy of economic losses across sectors is essential for assessing tradeoffs between water supply and environmental health of sensitive natural areas and/or water bodies.

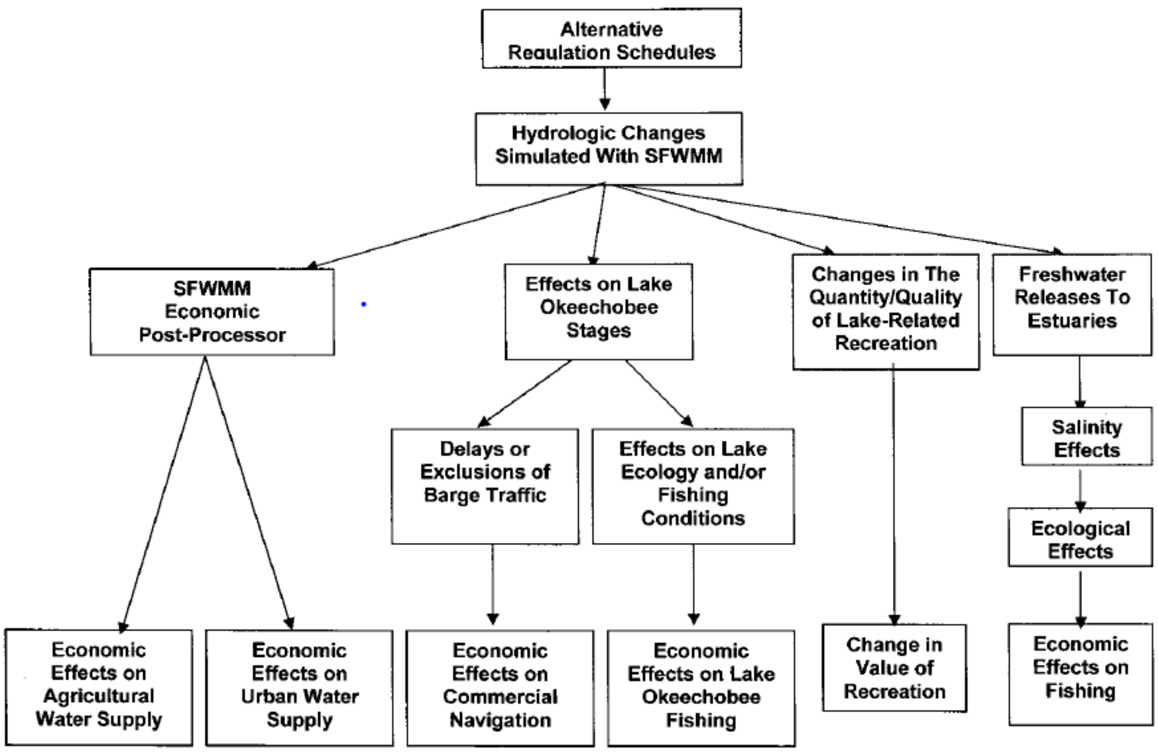


FIGURE 1-4
SOURCES OF ECONOMIC EFFECTS

Figure V-3. Sources of economic effects (reproduced from USACE 2007).

Although Figure V-3 represents a good initial framework for economic assessment, it needs to be expanded with input from historic data on economic losses and/or gains. It should also be enhanced to include impacts of changes in human health, real estate, and tourism on the regional economy caused by water quantity/water quality/ecological impacts of Lake Okeechobee operations. Additional tools for representing such impacts are needed to assess the overall economic effects.

In summary, improved economic models and economic performance measures for all system objectives (e.g., water supply, flood control, navigation, ecological restoration/protection, as well as impacts to human health, tourism and real estate) are needed to help analyze tradeoffs more quantitatively and transparently. In addition, all performance measures should be systematically compared to observed/historic ecosystem performance and economic impacts to ensure their validity. Finally, in view of future climate change and sea level rise, metrics representing various management objectives may evolve over time. Such non-stationarity should be considered in the evaluation of alternatives, by comparing the temporal evolution of performance metrics, in addition to summary statistics over wet and dry decades within the specific simulation periods and the entire period of simulation. This analysis could help determine whether performance measures designed to restore 20th-century hydrology and ecosystems will be achievable under future climate and sea level rise conditions.

Tradeoffs and Decision Making

LORS2008, and its predecessor WSE, are among the most complex large-lake management strategies in the United States. Both the planning and operational phases of LORS2008 use climate outlooks for management guidance and this is not typically found in “rule curves” used for managing reservoirs elsewhere in the country. The extensive use of performance metrics to “balance” the multiple, but conflicting objectives of water management, at times using optimization techniques, is also unique. However, this balance to achieve the “best operational compromise” (USACE 2007), is heavily influenced by the subset of possible metrics selected, extensive constraints (some of which are legal), basic assumptions such as period of simulation, the amount of system-wide storage assumed in the design of the schedule, and the assumed relationship between hydrologic performance measures and ecological and economic response.

In previous planning efforts, the goal was to achieve the best operational compromise, considering multiple conflicting objectives. The approach apparently assumed “equal” weights for the subset of all possible objectives represented by potentially non-commensurate Performance Measures. The “best operational compromise” leads to a form of shared adversity that may not be ideal for sustainability of subsystems (e.g., estuaries) affected by the management of Lake Okeechobee and does not consider other important factors that all stakeholders value. Balancing objectives with equal, static weights and simple hydrologic surrogates for water quality and ecology may produce inferior outcomes.

An alternative approach would be to assess the status of each subsystem served by Lake Okeechobee and develop a policy framework that takes antecedent conditions and resilience into account, possibly favoring protection of those in poor state, and developing a corresponding weighting scheme for optimizing the performance according to that policy call. Such a decision would require careful consideration of legal constraints, and tradeoffs with accurately verified Performance Measures. In addition, adaptation strategies to mitigate undesirable impacts on other objectives, such as crop insurance to compensate for losses caused by inadequate agricultural water supply, or payment for environmental services associated with temporary storage of flood waters on private lands, could be considered.

The Technical Review Team recognizes that the myriad operational rules associated with Lake Okeechobee management, variable and changing climate, and the current physical realities of the system, make the LOSOM development extremely challenging. The public, and in some cases, those who make important decisions, do not always appreciate the constraints agencies face when they attempt to balance objectives. Over the years, the South Florida water system has been subject to anthropogenic influences, such as excessive loading of nutrients from tributary watersheds, and many of the constraints are a consequence of the physical reality that arose from historical decisions and impacts that accumulated over many decades. For instance, there are excessive legacy nutrients in Lake Okeechobee, with more continuing to enter from tributaries. No lake operation schedule can mitigate such influences until significant additional water storage and treatment infrastructure is designed, built and operational. In the meantime, undesirable water quality and ecological impacts from both internal and external nutrient loading will continue for some time. For these reasons, there may not be a best “operational compromise” going forward and tradeoffs among conflicting objectives may need to be viewed differently, since there will be periodic winners and losers as a consequence of any regulation decision. Clearly, such a process should be transparent, consider legal restrictions, and include a proactive outreach program to inform the public of the constraints associated with water release decisions. Furthermore, efforts should be made to manage expectations regarding changes in operational outcomes that will result from the new LOSOM.

Recommendations

<u>Improved Predictive Tools:</u>

- Significant progress has been made to develop hydrodynamic/hydrologic, water quality, and ecological models that can simulate environmental performance of alternative regulation schedules. The next LOSOM development could benefit significantly from using such tools in both the Planning and Operational phases. During the Planning phase, they could provide direct simulation of impacts of various proposed alternative operating schedules on both water quality and ecology in Lake Okeechobee, as well as the St. Lucie and Caloosahatchee Estuaries. For real time operation, these modeling tools could provide valuable information for making release decisions. In particular, incorporation of new modeling tools may be useful to incorporate water quality and ecological antecedent conditions and forecasts into LOSOM release guidance flowcharts more quantitatively, and to broaden the use of Position Analysis to include outlooks of the water quality and ecological performance over ensuing seasons and beyond.

- Improved economic models and analysis of economic performance measures for all system objectives (e.g., water supply, flood control, navigation, ecological restoration/protection as well as new performance measures for impacts to endangered species, human health, tourism and real estate) are needed to help analyze tradeoffs more quantitatively and transparently.

Improved Performance Measures:

- Simplified, event-based hydrologic surrogates for lake and estuarine ecological performance measures used in LORS2008 planning should be enhanced. The improved predictive tools described above should be used to develop more sophisticated hydrologic measures that better take into account antecedent hydrologic/ecologic conditions; the timing, duration, frequency and return interval of events; and variable resilience of ecosystem components.
- The sensitivity of all performance measures to climate variability, climate change and sea level rise should be considered. This should include evaluation of the temporal trends of performance measures over projected climate and sea level rise scenarios, in addition to summary statistics over decadal climate sequences and the entire period of historical record.
- All hydrologic, ecologic and economic performance measures should be systematically compared to observed/historic ecosystem performance and economic impacts to ensure their validity.

Decision Making Frameworks and Communication:

- A multi-objective optimization framework that considers equal, temporally constant weights for all system objectives (water supply, flood control, lake ecology, estuary ecology, Everglades Protection Area ecology) may produce inferior results. Other approaches that systematically vary system objective weights based on antecedent conditions and variable resilience among system components (agricultural and urban areas, tourism and real estate, human health, lake ecology, estuarine ecology, STA performance, WCA ecology) may yield better overall long-term performance of the system.
- An outreach program to inform the public of the constraints associated with water release decisions should be developed and implemented. This program should acknowledge that both external and internal nutrient loads are likely to remain high during implementation of the next LOSOM, leading to future cyanobacteria blooms, and constraining the amount of water that can be released southward. It should be made clear that water-release decisions will always involve trade-offs that result in “winners and losers,” but that all stakeholders interests will be considered as quantitatively and transparently as possible.

VI. List of Abbreviations

acre-ft	acre-feet
AMO	Atlantic Multidecadal Oscillation
AMSL	Above Mean Sea Level
AP	Adaptive Protocols
BMAP	Basin Management Action Plan
BMP	Best Management Practice
$CaCO_3$	Calcium Carbonate
cfs	cubic feet per second
C&SF	Central and Southern Florida Project
CEPP	Central Everglades Planning Project
CERP	Comprehensive Everglades Restoration Plan
CH3D	Curvilinear-grid Hydrodynamics model in three-dimensions (3D)
chl *a*	Chlorophyll *a*
cm	Centimeters
CMIP5	Climate Model Intercomparison Project 5
CPC	Climate Perdition Center
CRE	Caloosahatchee River and Estuary
DPM	Decomp Physical Model
DIN	Dissolved Inorganic Nitrogen
DO	Dissolved Oxygen
DRP	Dissolved Reactive Phosphorus
EAA	Everglades Agricultural Area
ENP	Everglades National Park
ENSO	El Niño Southern Oscillation
EPA	Everglades Protection Area
EPP	Economic Post Processor
ESA	Endangered Species Act
ET	Evapotranspiration
FDEP	Florida Department of Environmental Protection
ft	feet
FWC	Florida Fish and Wildlife Conservation Commission
g	gram
GHG	Green House Gases

ha	hectare
HAB	Harmful Algal Bloom
HCl	Hydrochloric Acid
HIS	Habitat Suitability Index
HHD	Herbert Hoover Dike
HSPF	Hydrologic Simulation Program Fortran
IRL	Indian River Lagoon
KCl	Potassium Chloride
km	kilometer
km^2	square kilometers
LOEM	Lake Okeechobee Environment Model
LONIN	Lake Okeechobee Net Inflow
LONINO	Lake Okeechobee Net Inflow Outlook
LORS	Lake Okeechobee Regulation Schedule
LORS2008	2008 Lake Okeechobee Regulation Schedule
LOSOM	Lake Okeechobee System Operating Manual
m	meters
m^3	cubic meters
mlw	mean low water
mm	millimeter
m^3s^{-1}	cubic meters per second
mt	metric tons
mt yr^{-1}	metric tons per year
N	Nitrogen
NaOH	Sodium Hydroxide
NGVD	National Geodetic Vertical Datum
NMFS	National Marine Fisheries Service
NRCS	Natural Resources Conservation Service
ONI	Oceanic Niño Index
P	Phosphorus
PA	Position Analysis
PAR	Photosynthetically Active Radiation
PDO	Pacific Decadal Oscillation
Psu	practical salinity unit
SAV	Submerged Aquatic Vegetation

SEIS	Supplemental Environmental Impact Statement
SFWMD	South Florida Water Management District
SLE	St Lucie River and Estuary
SRP	Soluble Reactive Phosphorus
SST	Sea Surface Temperature
STA	Stormwater Treatment Area
t	ton
THC	Tributary Hydrologic Condition
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
USACE	U.S. Army Corps of Engineers
VEC	Valued Ecosystem Component
WASH123D	Watershed Model
WCA	Water Conservation Area
WCP	Water Control Plan
WSE	Water Supply and Environment Lake Okeechobee Regulation Schedule
yr	year

VII. Review Team Biographical Sketches

Mark Brenner, Ph.D., is Professor of Geological Sciences and Director of the Land Use and Environmental Change Institute (LUECI) at the University of Florida. He received his bachelor's degree in Biology from Grinnell College and his M.S. and Ph.D. degrees in Zoology from the University of Florida. He is a limnologist/paleolimnologist whose research focuses on long-term interactions among climate, environment, and humans in tropical and subtropical watersheds. In addition to his work on Florida lakes, he has conducted fieldwork in Mexico, Guatemala, Panama, Venezuela, Bolivia, Ecuador and the Galapagos Islands, Colombia, Haiti, Dominican Republic, China, Cambodia and Madagascar. Mark has served as Co-Editor-in-Chief of the *Journal of Paleolimnology* since 2007.

Wendy D. Graham, Ph.D., is the Carl S. Swisher Eminent Scholar in Water Resources in the Department of Agricultural and Biological Engineering at the University of Florida, and Director of the University of Florida Water Institute. She holds a bachelor's degree from the University of Florida in Environmental Engineering. Her PhD is in Civil and Environmental Engineering from the Massachusetts Institute of Technology. She conducts research in the areas of coupled hydrologic-water quality modeling; water resources evaluation and remediation; evaluation of impacts of agricultural production on surface and groundwater quality; and evaluation of impacts of climate variability and climate change on water resources. Dr. Graham is currently a member of the National Academy of Sciences Water Science and Technology Board, and was recently appointed by the Florida Governor to the State of Florida Blue Green Algae Task Force. She served as the Hydrologic Sciences Program Director for the National Science Foundation in 2015-2016, and as Chair of the University of Florida Agricultural and Biological Engineering Department from 2003-2006.

James W. Fourqurean, Ph.D., is a Professor of Biological Sciences and the Director of the Coastal Oceans Research Center in the Institute of Water and Environment at Florida International University. He also holds a visiting professor position at the University of Western Australia. He holds a bachelor's degree in Biology and Environmental Science from the University of Virginia, and he received his M.S. and Ph.D. in Environmental Science from University of Virginia. His research focuses on ecology of marine communities dominated by vascular plants, and how water quality and food web structure interact to determine ecological properties of these systems. Dr. Fourqurean currently serves as the President of the Coastal and Estuarine Research Federation, and he served as Chair of the Department of Biological Sciences at Florida International University from 2002-2006.

Charles A. Jacoby, Ph.D., is a Courtesy Associate Professor in the Soil and Water Sciences Department at the University of Florida and the Supervising Environmental Scientist for the

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Jayantha Obeysekera, Ph.D., P.E. is a Research Professor of Earth & Environment and the Director of the Sea Level Solutions Center in the Institute of Environment at the Florida International University. He holds a bachelor's degree in Civil Engineering from University of Sri Lanka, M. Eng. from University of Roorkee, India, and a Ph.D. in Civil Engineering from Colorado State University with specialization in water resources. Dr. Obeysekera served as a member of the federal advisory committee that directed the development of the National Climate Assessment in 2014. He was also a co-author of the sea level rise projections report published by NOAA for the National Climate Assessment and a lead author for the Southeast Chapter of the National Climate Assessment. Dr. Obeysekera also served as a member of the Coastal Assessment Regional Scenario Working Group associated with the Department of Defense in the United States. He is a recipient of the 2015 Norman Medal of the American Society of Civil Engineers for a technical paper that makes a definitive contribution in engineering.

VIII. References

Abal, E.G., N. Loneragan, P. Bowen, C.J. Perry, J.W. Udy, and W.C. Dennison. 1994. Physiological and morphological responses of the seagrass *Zostera capricorni* Ascher. to light intensity. Journal of Experimental Marine Biology and Ecology 178:113-129.

Ager, L.A. 1971. The fishes of Lake Okeechobee. Quarterly Journal of the Florida Academy of Sciences 34:53-62.

Aldridge, F.J., E.J. Phlips and C.L. Schelske. 1995. The use of nutrient enrichment bioassays to test for spatial and temporal distribution of limiting factors affecting phytoplankton dynamics in Lake Okeechobee, Florida. Archiv für Hydrobiologie, Advances in Limnology 4:177-190.

Antonini, G.A., D.A. Fann, and P. Roat. 2002. A Historical Geography of Southwest Florida Waterways Silver Spring, MD: National Seagrant College Program.

Arnold, T.E., M. Brenner, J.H. Curtis, A. Dutton, S.M. Baker, J.H. Escobar, and C.A. Ortega. 2014. Application of stable isotopes ($\delta^{18}O$) to determine growth patterns of the invasive gastropod *Pomacea maculata* in Florida lakes. Florida Scientist 77:126-143.

Atkinson, M.J., and S.V. Smith. 1983. C:N:P ratios of benthic marine plants. Limnology and Oceanography 28(3):568-574.

Aumen, N.G. and R.E. Wetzel (Eds.). 1995. Ecological studies on the littoral and pelagic systems of Lake Okeechobee, Florida (USA). Archiv für Hydrobiologie, Advances in Limnology 45, 356 p.

Bachmann, R.W., M.V. Hoyer, and D.E. Canfield, Jr. 2000. The potential for wave disturbance in shallow Florida lakes. Lake and Reservoir Management 16:281-291.

Badylak, S., E.J. Phlips, N. Dix, J. Hart, A. Srifa, D.E. Haunert, Z.L. He, J. Lockwood, P.J. Stoffella, D. Sun, and Y. Yang. 2016. Phytoplankton dynamics in a subtropical tidal creek: influences of rainfall and water residence time on composition and biomass. Marine and Freshwater Research 67:466-482.

Barnes, T. 2005. Caloosahatchee Estuary conceptual ecological model. Wetlands 25(4):884-897.

Barnes, T.K., A.K. Volety, K. Chartier, F.J. Mazzotti, and L. Pearlstine. 2007. A habitat suitability index model for the eastern oyster (Crassostrea virginica), a tool for restoration of the Caloosahatchee Estuary, Florida. Journal of Shellfish Research 26(4):949-959.

Barnes, M.A., R.K. Fordham, R.L. Burks, and J.J. Hand. 2008. Fecundity of the exotic apple snail, *Pomacea insularum*. Journal of the North American Benthological Society 27:738–745.

Beckler, J. S., et al. (2019). "Coastal Harmful Algae Bloom Monitoring via a Sustainable, Sail-Powered Mobile Platform." Frontiers in Marine Science **6**: 14.

Belmont, M.A., J.R. White, and K.R. Reddy. 2009. Phosphorus sorption and potential phosphorus storage in sediments of Lake Istokpoga and the upper chain of lakes, Florida, USA. Journal of Environmental Quality 38(3):987-996.

BEM & University of Florida. 2007. Lake Okeechobee Sediment Quality. Final Report to the South Florida Water Management District, West Palm Beach. 30 p.

Bennetts, R.E. and W. Kitchens. 1997. Demography and movements of snail kites in Florida. Technical Report 56, Florida Cooperative Fish and Wildlife Research Unit, Gainesville, FL.

Bertolotti, L., and P. Balci. 2012. Appendix 10-1: St. Lucie River Watershed Protection Plan Update, 2012 South Florida Environment Report. West Palm Beach, FL: South Florida Water Management District.

Black, K., M. Yilmaz and E.J. Phlips. 2011. Growth and toxin production by *Microcystis aeruginosa* PCC 7806 (Kutzing) Lemmerman at elevated salt concentrations. Journal Environmental Protection 2:669-674.

Bowes, G., T.K. Van, L.A. Garrard, and W.T. Haller. 1977. Adaptation to low light levels by Hydrilla. Journal of Aquatic Plant Management 15:32-35.

Boyer, J. N. 2006. Shifting N and P limitation along a north-south gradient of mangrove estuaries in south Florida. Hydrobiologia 569:167-177.

Brenner, M., M.W. Binford, and E.S. Deevey. 1990. Lakes. In: R.L. Myers and J.J. Ewel (Eds.), Ecosystems of Florida (p. 364-391). Orlando, FL: University of Central Florida Press.

Brenner, M. D.A. Hodell, J.H. Curtis, W.F. Kenney, B. Gu, J.M. Newman, and B.W. Leyden. 2006. Mechanisms for organic matter and phosphorus burial in sediments of a shallow, subtropical, macrophyte-dominated lake. Journal of Paleolimnology 35:129-148.

Brezonik, P.L., and D.R. Engstrom. 1998. Modern and historic accumulation rates of phosphorus in Lake Okeechobee, Florida. Journal of Paleolimnology 20:31-46.

Brooks, H.K. 1974. Lake Okeechobee. In: P.J. Gleason (Ed.), Environments of South Florida: Present and Past (p. 256-284). Miami, FL: Miami Geological Society.

Brown, C.D., M.V. Hoyer, R.W. Bachmann, and D.E. Canfield, Jr. 2000. Nutrient-chlorophyll relationships: an evaluation of empirical nutrient-chlorophyll models using Florida and north-temperate lake data. Canadian Journal of Fisheries and Aquatic Sciences 57:1574-1583.

Brown, C., W. Werick, W. Leger, and D. Fay, 2011. A decision-analytic approach to managing climate risks: application to the Upper Great Lakes. Journal of the American Water Resources Association (JAWRA) 47(3):524-534. DOI: 10.1111/j.1752-1688.2011.00552.

Bull, L.A., D.D. Fox, D.W. Brown, L.J. Davis, S.J. Miller, and J.J. Wullschleger. 1995. Fish distribution in limnetic areas of Lake Okeechobee, Florida. Archiv fur Hydrobiologie, Advances in Limnology 45:333-342.

Buzzelli, C., P. Gorman, P.H. Doering, Z.Q. Chen, and Y.S. Wan. 2015. The application of oyster and seagrass models to evaluate alternative inflow scenarios related to Everglades restoration. Ecological Modelling 297:154-170.

Caccia, V.G., and J.N. Boyer. 2007. A nutrient loading budget for Biscayne Bay, Florida. Marine Pollution Bulletin 54:994-1008.

Campbell, J.E., and J.W. Fourqurean. 2009. Interspecific variation in the elemental and stable isotopic content of seagrasses in South Florida. Marine Ecology Progress Series 387:109-123.

Cattau, C.E. 2010. Effects of an exotic prey species on a native specialist: example of the snail kite. Biological Conservation 143:513–520.

Cattau, C.E., R.J. Fletcher Jr., B.E. Reichert, and W.M. Kitchens. 2016. Counteracting effects of a non-native prey on the demography of a native predator culminate in positive population growth. Ecological Applications 26:1952–1968.

Cattau, C.E., R.J. Fletcher Jr., R.T. Kimball, C.W. Miller, and W.M. Kitchens. 2018. Rapid morphological change of a top predator with the invasion of a novel prey. Nature Ecology & Evolution 2:108-115.

Chamberlain, R., and D. Hayward. 1996. Evaluation of water quality and monitoring in the St. Lucie estuary, Florida. Water Resources Bulletin 32(4):681-696.

Chamberlain, R.H. and P.H. Doering. 1998. Freshwater inflow to the Caloosahatchee Estuary and the resource-based method for evaluation. In Proceedings of the Charlotte Harbor Public Conference and Technical Symposium. Punta Gorda, FL: Charlotte Harbor National Estuary Program.

Chang, S.J., W. Graham, J. Geurink, N. Wanakule, and T. Asefa. 2018. Evaluation of impacts of future climate change and water use scenarios on regional hydrology. Hydrology and Earth System Sciences 22:4793-4813.

Chastant, J.E., M.L. Peterson, and D.E. Gawlik. 2017. Nesting substrate and water-level fluctuations influence wading bird nesting patterns in a large shallow eutrophic lake. Hydrobiologia 788:371-383.

Chen, R., and R.R. Twilley. 1999. Patterns of mangrove forest structure and soil nutrient dynamics along the Shark River Estuary, Florida. Estuaries 22(4):955-970.

Cooper, L.W., and M.J. DeNiro. 1989. Stable carbon isotope variability in the seagrass Posidonia oceanica: evidence for light intensity effects. Marine Ecology Progress Series 50:225-229.

Corbett, C.A., P.H. Doering, K.A. Madley, J.A. Ott, and D.A. Tomasko. 2005. Using seagrass coverage as an indicator of ecosystem condition. In: S.A. Bortone (Ed.), Estuarine Indicators (p. 531). Boca Raton: CRC Press.

David, P.G. 1994a. Wading bird nesting at Lake Okeechobee, Florida: an historic perspective. Colonial Waterbirds 17:69-77.

David, P.G. 1994b. Wading bird use of Lake Okeechobee relative to fluctuating water levels. Wilson Bulletin 106:719-732.

Dayton, P.K. 1972. Toward an understanding of community resilience and the potential effects of enrichments to the benthos at McMurdo Sound, Antarctica. In: B.C. Parker (Ed.), Proceedings of the Colloquium on Conservation Problems in Antarctica (p. 81-95). Lawrence, KS: Allen Press.

Dessalegne, T., J. Obeysekera, S. Nair, and J. Barnes. 2016. Assessment of CMIP5 multi-model dataset to evaluate impacts on the future regional water resources of South Florida. Paper presented at the World Environmental and Water Resources Congress 2016.

Dessue S., R.M. Price, T.G. Troxler, and J.S. Kominiski. 2018. Effects of sea-level rise and freshwater management on long-term water levels and water quality in the Florida Coastal Everglades. Journal of Environmental Management 211:164-176.

Dial Cordy and Associates Inc. 2011. Benthic Habitat Mapping and Substrate Characterization in the Northern Estuaries, Florida. Final report prepared for Jacksonville District, US Army Corps of Engineers. Jacksonville.

Doering, P.H. 1996. Temporal variability of water quality in the St. Lucie Estuary, south Florida. Water Resources Bulletin 32:1283-1305.

Doering, P.H., R.H. Chamberlain, and D.E. Haunert. 2002. Using submerged aquatic vegetation to establish minimum and maximum freshwater inflows to the Caloosahatchee estuary, Florida. Estuaries 25(6B):1343-1354.

Doering, P.H., and Y.S. Wan. 2018. Ecohydrological controls on blue crab landings and minimum freshwater inflow to the Caloosahatchee Estuary, Florida. Wetlands Ecology and Management 26(2):161-174.

Donar, C., E.F. Stoermer, and M. Brenner. 2009. The Holocene paleolimnology of Lake Apopka, Florida. Nova Hedwigia, Beiheft 135:58-71.

Doss-Gollin, J., Farnham, D.J., S. Steinschneider, and U. Lall. 2019.Robust adaptation to multiscaleclimate variability. Earth's Future 7:734–747. https://doi.org/10.1029/2019EF001154

Dreher, T.W., L.P. Collart, R.S. Mueller, K.H. Halsey, R.J. Bildfell, P. Schreder, A. Sobhakumari, and R. Ferry. 2019. *Anabaena/Dolichospermumas* the source of lethal microcystin levels responsible for a large cattle toxicosis event. Toxicon X(1):100003.

Duarte, C.M. 1990. Seagrass nutrient content. Marine Ecology Progress Series 67:201-207.

Duarte, C.M. 1992. Nutrient concentrations of aquatic plants: patterns across species. Limnology and Oceanography 37(4):882-889.

Duarte, C.M. 1995. Submerged aquatic vegetation in relation to different nutrient regimes. Ophelia 41:87-112.

Dunne, E.J., M.W. Clark, R. Corstanje, and K.R. Reddy. 2011. Legacy phosphorus in subtropical wetland soils: Influence of dairy, improved and unimproved pasture land use. Ecological Engineering 37:1481-1491.

Elser, J.J., M.E.S. Bracken, E.E. Cleland, D.S. Gruner, W.S. Harpole, H. Hillebrand, J.T. Ngai, E.W. Seabloom, J.B. Shurin, and J.E. Smith. 2007. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecology Letters 10(12):1135-1142.

Enfield D.B., A.M. Nunez, and P.J. Trimble. 2001. The AMO and its relationship to rainfall and river flow in the continental US. Geophysical Research Letters 28(10):2077-2080.

Engstrom, D.R., S.P. Schottler, P.R. Leavitt, and K.E. Havens. 2006. A re-evaluation of the cultural eutrophication of Lake Okeechobee, Florida using multiproxy sediment records. Ecological Applications 16:1194–1206.

FDEP. 2008. Nutrient and dissolved oxygen TMDL for the St. Lucie Basin. Florida Department of Environmental Protection, Tallahassee, Florida.

FDEP. 2009. FINAL TMDL report: Nutrient TMDL for the Caloosahatchee Estuary, Ed. F.D.E.P. South District. Tallahassee: Florida Department of Environmental Protection.

FDEP. 2012. Final Caloosahatchee Estuary Basin Management Plan, Ed. Florida Department of Environmental Protection. Tallahassee.

Fisher, M.M., K.R. Reddy, and R.T. James. 2001. Long-term changes in the sediment chemistry of a large shallow subtropical lake. Lake and Reservoir Management 17:217-232.

Fisher, M.M., K.R. Reddy, and R.T. James. 2005. Internal nutrient loads from sediments in a shallow, subtropical lake. Lake and Reservoir Management 21:338-349.

Fletcher, R., C. Poli, E. Robertson, B. Jeffery, S. Dudek, and B. Reichert. 2017. Snail Kite Demography. 2016 Annual Report. Prepared for the USACE and Florida FWC. USGS Florida Cooperative Fish and Wildlife Research Unit, University of Florida, Gainesville.

Fourqurean, J.W., J.C. Zieman, and G.V.N. Powell. 1992. Phosphorus limitation of primary production in Florida Bay: Evidence from the C:N:P ratios of the dominant seagrass *Thalassia testudinum*. Limnology and Oceanography 37(1):162-171.

Fourqurean, J.W., R.D. Jones, and J.C. Zieman. 1993. Processes influencing water column nutrient characteristics and phosphorus limitation of phytoplankton biomass in Florida Bay, FL, USA: inferences from spatial distributions. Estuarine, Coastal and Shelf Science 36:295-314.

Fourqurean, J.W., G.V.N. Powell, W.J. Kenworthy, and J.C. Zieman. 1995. The effects of long-term manipulation of nutrient supply on competition between the seagrasses *Thalassia testudinum* and *Halodule wrightii* in Florida Bay. Oikos 72:349-358.

Fourqurean, J.W., and M.B. Robblee. 1999. Florida Bay: a history of recent ecological changes. Estuaries 22(2B):345-357.

Fourqurean, J.W., and L.M. Rutten. 2003. Competing goals of spatial and temporal resolution: monitoring seagrass communities on a regional scale. In: D.E. Busch, and J.C. Trexler

(Eds.), Monitoring ecosystem initiatives: interdisciplinary approaches for evaluating ecoregional initiatives (p. 257-288). Washington, D.C.: Island Press.

Fourqurean, J.W., S.A. Manuel, K.A. Coates, S.C. Massey, and W.J. Kenworthy. 2019. Decadal monitoring in Bermuda shows a widespread loss of seagrasses attributable to overgrazing by the green sea turtle *Chelonia mydas*. Estuaries and Coasts 42:1524-1540.

Fry, B., P.L. Mumford, D.D. Fox, G.L. Warren, K.E. Havens, and A.D. Steinman. 1999. Trophic position and individual feeding histories of fish from Lake Okeechobee, Florida. Canadian Journal of Fisheries and Aquatic Sciences 56:590-600.

FWC, Seagrass Integrated Mapping and Monitoring Program Mapping and Monitoring Report No. 3. https://myfwc.com/research/habitat/seagrasses/projects/active/simm/simm-reports/

Gallegos, C.L., and W.J. Kenworthy. 1996. Seagrass depth limits in the Indian River Lagoon (Florida, USA): Application of an optical water quality model. Estuarine, Coastal and Shelf Science 42:267-288.

Gimenez, C.A. 2019. Report of the findings of the County's study on the decline of seagrass and hardbottom habitat in Biscayne Bay - Directive No. 171537, Ed. Miami-Dade County Division of Environmental Resources Management. Miami.

Graham, W.D., M.J. Angelo, T.K. Frazer, P.C. Frederick, K.E. Havens, and K.R. Reddy. 2015. Options to Reduce High Volume Freshwater Flows to the St. Lucie and Caloosahatchee Estuaries and Move More Water from Lake Okeechobee to the Southern Everglades. Report commissioned by the State of Florida Senate. University of Florida, Gainesville, FL.

Grimshaw, H.J., K.E. Havens, B. Sharfstein, A. Steinman, D. Anson, T. East, R.P. Maki, A. Rodusky, and K.R. Jin. 2002. The effects of shading on morphometric and meristic characteristics of *Vallisneria americana* transplants from Lake Okeechobee, Florida. Archiv fur Hydrobiologie, Advances in Limnology 155:65-81.

Hall, M.O., B.T. Furman, M. Merello, and M.J. Durako. 2016. Recurrence of *Thalassia testudinum* seagrass die-off in Florida Bay, USA: initial observations. Marine Ecology Progress Series 560:243-249.

Harke, M.J., M.M. Steffen, C.J. Gobler, T.G. Otten, S.W. Wilhelm, S.A. Wood, and H.W. Paerl. 2016. A review of the global ecology, genomics, and biogeography of the toxic cyanobacterium, *Microcystis* spp. Harmful Algae 54:4-20.

Harris, B.A., K.D. Haddad, K.A. Steidinger, and J.A. Huff. 1983. Assessment of fisheries habitat: Charlotte Harbor and Lake Worth, Florida, Ed. Bureau of Marine Research Florida Department of Natural Resources. St. Petersburg, FL: FDNR.

Harrison, P.J., M.H. Hu, Y.P. Yang, and X. Lu. 1990. Phosphate limitation in estuarine and coastal waters of China. Journal of Experimental Marine Biology and Ecology 140:79-87.

Harwell, M.C., and K.E. Havens. 2003. Experimental studies on the recovery potential of submerged aquatic vegetation after flooding and desiccation in a large subtropical lake. Aquatic Botany 77:135-151.

Harwell, M.C. and B. Sharfstein. 2009. Submerged aquatic vegetation and bulrush in Lake Okeechobee as indicators of greater Everglades ecosystem restoration. Ecological Indicators 9S:S46-S55.

Haunert, D.E., and J.R. Startzman. 1985. Short term effects of a freshwater discharge on the biota of the St. Lucie Estuary, Florida. West Palm Beach, FL: South Florida Water Management District.

Haunert, D.E. 1988. Sedimentation characteristics and toxic substances in the St. Lucie Estuary, Florida. West Palm Beach, FL: South Florida Water Management District.

Havens, K.E. 1995. Secondary nitrogen limitation in a subtropical lake impacted by non-point source agricultural pollution. Environmental Pollution 89(3): 241-246.

Havens, K., N.G. Aumen, R.T. James, and V. Smith. 1996. Rapid ecological changes in a large subtropical lake undergoing cultural eutrophication. Ambio 25:150-155.

Havens, K.E., J. Hauxwell, A.C. Tyler, S. Thomas, K.J. McGlathery, J. Cebrian, I. Valiela, A.D. Steinman, and S-J Hwang. 2001. Complex interactions between autotrophs in shallow marine and freshwater ecosystems: implications for community responses to nutrient stress. Environmental Pollution 113:95-107.

Havens, K.E., M.C. Harwell, M.A. Brady, B. Sharfstein, T.L. East, A.J. Rodusky, D. Anson, and R.P. Maki. 2002. Large-scale mapping and predictive modeling of submerged aquatic vegetation in a shallow eutrophic lake. The Scientific World Journal 2:49-965.

Havens, K.E., and W.W. Walker. 2002. Development of a total phosphorus concentration goal in the TMDL process for Lake Okeechobee, Florida (USA). Lake and Reservoir Management 18:227-238.

Havens, K.E. 2003. Submerged aquatic vegetation correlations with depth and light attenuating materials in a shallow subtropical lake. Hydrobiologia 493:173-186.

Havens, K.E., B. Sharfstein, M.A. Brady, T.L. East, M.C. Harwell, R.P. Maki, and A.J. Rodusky. 2004. Recovery of submerged plants from high water stress in a large subtropical lake in Florida, USA. Aquatic Botany 78:67-82.

Havens, K.E. and D.E. Gawlik. 2005. Lake Okeechobee conceptual ecological model. Wetlands 25:908–925.

Havens, K.E., D. Fox, S. Gornak, and C. Hanlon. 2005. Aquatic vegetation and largemouth bass population responses to water-level variations in Lake Okeechobee, Florida (USA). Hydrobiologia 539:225-237.

Havens, K.E., K.R. Jin, N. Iricanin, and R.T. James. 2007. Phosphorus dynamics at multiple time scales in the pelagic zone of a large shallow lake in Florida, USA. Hydrobiologia 581:25-42.

Havens, K.E., J.R. Beaver, D.A. Casamatta, T.L. East, R.T. James, P. McCormick, E.J. Phlips, and A.J. Rodusky. 2011. Hurricane effects on the planktonic food web of a large subtropical lake. Journal of Plankton Research 33:1081-1094.

Havens, K.E., and A.D. Steinman. 2015. Ecological responses of a large shallow lake (Okeechobee, Florida) to climate change and potential future hydrologic regimes. Environmental Management 55:763-775.

Havens, K.E., H. Paerl, E. Phlips, M. Zhu, J. Beaver, and A. Srifa. 2016. Extreme weather events and climate variability provide a lens to how shallow lakes may respond to climate change. Water 8, 229; doi:10.3390/w8060229.

Heil, C.A., M. Revilla, P.M. Glibert, and S. Murasko. 2007. Nutrient quality drives differential phytoplankton community composition on the southwest Florida shelf. Limnology and Oceanography 52(3):1067-1078. doi:10.4319/lo.2007.52.3.1067.

Hoffacker, V.A. 1994. 1993 Caloosahatchee River submerged grass observations. W. Dexter Bender and Associates, Inc. Report and Map, Ed. Ft. Meyers Service Center South Florida Water Management District. Ft. Meyers.

Howarth, R.W. 1988. Nutrient limitation of net primary production in marine ecosystems. Annual Review of Ecology and Systematics 19:89-110.

Hu, X.P., D.J. Burdige, and R.C. Zimmerman. 2012. delta C-13 is a signature of light availability and photosynthesis in seagrasses. Limnology and Oceanography 57:441-448.

Hu, C. M. and L. Feng (2016). "Modified MODIS fluorescence line height data product to improve image interpretation for red tide monitoring in the eastern Gulf of Mexico." Journal of Applied Remote Sensing 11: 14.

Hwang, S.J., K.E. Havens, and A.D. Steinman. 1999. Phosphorus kinetics of planktonic and benthic assemblages in a shallow subtropical lake. Freshwater Biology 40:729-745.

Irizarry, M. 2017. Lake Okeechobee Inflows Projected from Climatic Conditions. Report deliver to SFWMD (PO # 4500096303)

Irizarry M., J. Obeysekera, and T. Dessalegne. 2018. LOCA Analysis: Supplement to Determination of Future Intensity-Duration-Frequency Curves for Level of Service Planning Projects”, Technical Report, SFWMD, West Palm Beach, FL.

Ishman, S.E., T.M. Cronin, G.L. Brewter-Wingard, D.A. Willard, and D.J. Verardo. 1998. A record of ecosystem change, Manatee Bay, Barnes Sound, FL. Journal of Coastal Research 26:125-138.

James, R.T., V.J. Bierman Jr., M.J. Erickson, and S.C. Hinz. 2005. The Lake Okeechobee water quality model (LOWQM) enhancements, calibration, validation and analysis. Lake and Reservoir Management 21:231-260.

James, R.T., M.J. Chimney, B. Sharfstein, D.R. Engstrom, S.P. Schottler, T. East, and K.R. Jin. 2008. Hurricane effects on a shallow lake ecosystem, Lake Okeechobee, Florida (USA). Archiv für Hydrobiologie, Advances in Limnology 172:273-287.

Ji, Z.G. and K.R. Jin. 2006. Gyres and seiches in a large and shallow lake. Journal of Great Lakes Research 32:764-775.

Ji, Z.G. and K.R. Jin. 2014. Impacts of wind waves on sediment transport in a large, shallow lake. Lakes and Reservoirs: Research and Management 19:118-129.

Jin, K.R., and Z.G. Ji. 2001. Calibration and verification of a spectral wind–wave model for Lake Okeechobee. Ocean Engineering 28:571-584.

Jin, K.R., and D. Sun. 2007. Sediment resuspension and hydrodynamics in Lake Okeechobee during the late summer. Journal ASCE Engineering 133:899-910.

Jin, K.R., N.B. Chang, Z.G. Ji, and R.T. James. 2011. Hurricanes affect the sediment and environment in Lake Okeechobee. Critical Reviews in Environmental Science and Technology 41:382-394.

Jin, K.R., and Z.G. Ji. 2013. A long term calibration and verification of a submerged aquatic vegetation model for Lake Okeechobee. Ecological Processes 2:23.

Johnson, S.G., M.S. Allen, and K.E. Havens. 2007. A review of littoral vegetation, fisheries and wildlife responses to hydrologic variation at Lake Okeechobee. Wetlands 27:110-126.

Jones, J.R, and R.W. Bachmann. 1976. Prediction of phosphorus and chlorophyll levels in lakes. Journal of the Water Pollution Control Federation 48:2176-2182.

Julian, P., and T.Z. Osborne. 2018. From lake to estuary, the tale of two waters: a study of aquatic continuum biogeochemistry. Environmental Monitoring and Assessment 190:96. https://doi.org/10.1007/s10661-017-6455-8.

Kenworthy, W.J., and S. Dipiero. 1991. The distribution, abundance, and ecology of *Halophila johnsonii*, *Halophila decipiens*, and other seagrasses in the lower Indian River, FL. Annual report for FY 90, Ed. N.M.F.S. Office of Protected Resources, NOAA. Silver Spring, MD: National Oceanic and Atmospheric Administration.

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

Kramer, B.J., T.W. Davis, K.A. Meyer, B.H. Rosen, J.A. Goleski, G.J. Dick, G. Oh, and C.J. Gobler. 2018. Nitrogen limitation, toxin synthesis potential, and toxicity of cyanobacterial populations in Lake Okeechobee and the St. Lucie River Estuary, Florida, during the 2016 state of emergency event. Plos One 13(5):e0196278.

Kwon, H.H., U. Lall, and J. Obeysekera. 2009. Simulation of daily rainfall scenarios with interannual and multidecadal climate cycles for South Florida. Stochastic Environmental Research and Risk Assessment 23:879-896. https://doi.org/10.1007/s00477-008-0270-2

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

Lapointe, B.E., and B.J. Bedford. 2007. Drift rhodophyte blooms emerge in Lee County, Florida, USA: Evidence of escalating coastal eutrophication. Harmful Algae 6(3):421-437.

Lapointe, B.E., L.W. Herren, and B.J. Bedford. 2012. Effects of hurricanes, land use, and water management on nutrient and microbial pollution: St. Lucie Estuary, Southeast Florida. Journal of Coastal Research 28(6):1345-1361.

Lapointe, B.E., L.W. Herren, and A.L. Paule. 2017. Septic systems contribute to nutrient pollution and harmful algal blooms in the St. Lucie Estuary, Southeast Florida, USA. Harmful Algae 70:1-22.

Larios Mendieta, K., S. Gerber, and M. Brenner. 2018. Florida wildfires during the Holocene Climatic Optimum (9000-5000 cal yr BP). Journal of Paleolimnology 60:51-66.

Lempert, R. 2013. Scenarios that illuminate vulnerabilities and robust responses. Climatic Change 117:627-646.

Lin, Y.J., Z.L. He, Y.G. Yang, P.J. Stoffella, E.J. Phlips, and C.A. Powell. 2008. Nitrogen versus phosphorus limitation of phytoplankton growth in Ten Mile Creek, Florida, USA. Hydrobiologia 605:247-258.

Lirman, D., T. Thyberg, R. Santos, S. Schopmeyer, C. Drury, L. Collado-Vides, S. Bellmund, and J. Serafy. 2014. SAV communities of Western Biscayne Bay, Miami, Florida, USA: human and natural drivers of seagrass and macroalgae abundance and distribution along a continuous shoreline. Estuaries and Coasts 37(5):1243-1255.

Marshall, F.E., G.L. Wingard, and P.A. Pitts. 2014. Estimates of natural salinity and hydrology in a subtropical estuarine ecosystem: implications for greater everglades restoration. Estuaries and Coasts 37(6):1449-1466.

McClelland, J.W., I. Valiela, and R.H. Michemer. 1997. Nitrogen-stable isotope signatures in estuarine food webs: a record of increasing urbanization in coastal watersheds. Limnology and Oceanography 42:930-937.

McMahon, K., C. Collier, and P.S. Lavery. 2013. Identifying robust bioindicators of light stress in seagrasses: A meta-analysis. Ecological Indicators 30:7-15.

McMillan, C., and F.N. Moseley. 1967. Salinity tolerances of five marine spermatophytes of Redfish Bay, Texas. Ecology 48(3):503-506.

Milbrandt, E.C., L. Reidenbach, and M. Parsons. 2019. Determining the sources of macroalgae during beach stranding events from species composition, stable isotope analysis, and laboratory experiments. Estuaries and Coasts 42(3):719-730.

Miller, S.J., D.D. Fox, L.A. Bull, and T.D. McCall. 1990. Population dynamics of black crappie in Lake Okeechobee, Florida, following suspension of commercial harvest. North American Journal of Fisheries Management 10:98-105.

Millette, N.C., C. Kelble, A. Linhoss, and L. Visser. 2019. Using spatial variability in the rate of change of chlorophyll a to improve water quality management in a subtropical oligotrophic estuary. Estuaries and Coasts 42(7):1792-1803.

National Academies of Sciences, Engineering, and Medicine. 2018. Progress Toward Restoring the Everglades: The Seventh Biennial Review - 2018. Washington, DC: The National Academies Press. https://doi.org/10.17226/25198.

Nelson, N.G., R. Muñoz-Carpena, D. Kaplan and E.J. Phlips. 2018. Machine learning and long-term observations reveal highly variable responses of cyanobacteria genera to nutrient pollution and biophysical factors. Environmental Science and Technology 52:3527-3535.

NMFS. 2002. Final recovery plan for Johnson's seagrass (*Halophila johnsonii Eiseman*) prepared by the Johnson's seagrass recovery team, Ed. National Marine Fisheries Service. Silver Spring, MD: National Atmospheric and Oceanic Administration.

Noe, G.B., D.L. Childers, and R.D. Jones. 2001. Phosphorus biogeochemistry and the impact of phosphorus enrichment: Why is the Everglades so unique? Ecosystems 4(7):603-624.

NRC. 2014. Progress Toward Restoring the Everglades: The Fifth Biennial Review—2014. Washington, DC: The National Academies Press.

NRC. 2018. Progress Toward Restoring the Everglades: The Seventh Biennial Review—2018. Washington, DC: The National Academies Pres.

Nuttle, W.K., J.W. Fourqurean, B.J. Cosby, J.C. Zieman, and M.B. Robblee. 2000. Influence of net freshwater supply on salinity in Florida Bay. Water Resources Research 36(7):1805-1822.

Obeysekera J., P. Trimble, C. Neidrauer, and L. Cadavid. 2007. Consideration of climate variability in water resources planning and operations – South Florida's experience. Paper presented at the World Environmental and Water Resources Congress: Restoring Our Natural Habitat.

Obeysekera, J., M. Irizarry, J. Park, J. Barnes, and T. Dessalegne. 2011. Climate change and its implication for water resources management in South Florida. Journal of Stochastic Environmental Research & Risk Assessment 25(4):495-516.

Obeysekera, J., J. Barnes, T. Dessalegne, and S. Nair. 2015. Climate change scenarios for CERP vulnerability assessment. Presentation to Science Coordinate Group Meeting, January 23.

Obeysekera, J., J. Barnes, and M. Nungesser. 2015. Predicting response of the greater Florida Everglades to climate change and future hydrologic regimes: climate sensitivity runs and regional hydrologic modeling. Environment Management 55(4):749-62.

Olila O.G., K.R. Reddy, and W.G. Harris. 1995. Forms and distribution of inorganic phosphorus in sediments of two shallow eutrophic lakes in Florida. Hydrobiologia 302:147-161.

Paerl, H.W., J.J. Joyner, A.R. Joyner, K. Arthur, V. Paul, J.M. O'Neil, and C.A. Heil. 2008. Co-occurrence of dinoflagellate and cyanobacterial harmful algal blooms in southwest Florida coastal waters: dual nutrient (N and P) input controls. Marine Ecology Progress Series 371:143-153.

Parsons, M.L. 2013. Caloosahatchee Science Workshop Synthesis Report - Final. In Caloosahatchee Science Workshop. Naples, FL: Coastal Watershed Institute, Florida Gulf Coast University.

Phillips, R.C., and R.M. Ingle. 1960. Report on the marine plants, bottom types and hydrography of the St. Lucie Estuary and adjacent Indian River, Florida. In Special Scientific Report

No. 4. St. Petersburg, FL: Florida State Board of Conservation Marine Laboratory Maritime Base.

Phlips, E.J., F.J. Aldridge, P. Hansen, P.V. Zimba, J. Ihnat, M. Conroy, and P. Ritter. 1993a. Spatial and temporal variability of trophic state parameters in a shallow subtropical lake (Lake Okeechobee, Florida, USA). Archiv für Hydrobiologie, Advances in Limnology 128:437-458.

Phlips, E.J., P.V. Zimba, M.S. Hopson, and T.L. Crisman. 1993b. Dynamics of the plankton community in submerged plant dominated regions of Lake Okeechobee, Florida, USA. Internationale Vereinigung für Theoretische und Angewandte Limnologie: Verhandlungen 25:423-426.

Phlips, E.J., and J. Ihnat. 1995. Planktonic nitrogen fixation in a shallow subtropical lake (Lake Okeechobee, Florida, USA). Archiv fur Hydrobiologie, Advances in Limnology 45:191-20.

Phlips, E.J., F.J. Aldridge, C.L. Schelske, and T.L. Crisman. 1995. Relationships between light availability, chlorophyll a, and tripton in a large, shallow, subtropical lake. Limnology and Oceanography 40:416-421.

Phlips E.J., M. Cichra, K. Havens, C. Hanlon, S. Badylak, B. Rueter, M. Randall and P. Hansen 1997. Relationships between phytoplankton dynamics and the availability of light and nutrients in a shallow sub-tropical lake. Journal of Plankton Research 19:319-342.

Phlips, E.J., S. Badylak, J. Hart, D. Haunert, J. Lockwood, H. Manley, K. O'Donnell, D. Sun, P. Viveros and M. Yilmaz. 2012. Climatic influences on autochthonous and allochthonous phytoplankton blooms in a subtropical estuary, St. Lucie Estuary, Florida, USA. Estuaries and Coasts 35:335-352.

Phlips, E.J., S. Badylak, N.G. Nelson, and K.E. Havens. 2019 (In review). Hurricanes, El Niño and harmful algal blooms in two sub-tropical Florida estuaries: Direct and indirect impacts. Scientific Reports.

Pollman, C.D., and R.T. James. 2011. A simple model of internal loading of phosphorus in Lake Okeechobee. Lake and Reservoir Management 27:15-27.

Powell, G.V.N., W.J. Kenworthy, and J.W. Fourqurean. 1989. Experimental evidence for nutrient limitation of seagrass growth in a tropical estuary with restricted circulation. Bulletin of Marine Science 44:324-340.

Powell, G.V.N., J.W. Fourqurean, W.J. Kenworthy, and J.C. Zieman. 1991. Bird colonies cause seagrass enrichment in a subtropical estuary: observational and experimental evidence. Estuarine, Coastal and Shelf Science 32:567-579.

Rajagopalan, B., and U. Lall. 1999. A *k*-nearest-neighbor simulator for daily precipitation and other weather variables. Water Resources Research 35(10):3089-3101.

Rawlings, T.A., K.A. Hayes, R.H. Cowie, and M. Collins. 2007. The identity, distribution, and impacts of non-native apple snails in the continental United States. BMC Evolutionary Biology 7:97-111.

RECOVER 2007. CERP System-side Performance Measure, Northern Estuary Salinity Envelope Documentation Sheet.

Reddy, K.R., S. Newman, T.Z. Osborne, J.R. White, and H.C. Fitz. 2011. Phosphorus cycling in the Everglades ecosystem: legacy phosphorus implications for management and restoration. Critical Reviews in Environmental Science and Technology 41:149–186.

Redfield, A.C. 1958. The biological control of chemical factors in the environment. American Scientist 46:205-221.

Reichert, B.E., R.J. Fletcher, Jr., C.E. Cattau and W.M. Kitchens. 2016. Consistent scaling of population structure across landscapes despite intraspecific variation in movement and connectivity. Journal of Animal Ecology doi: 10.1111/1365-2656.12571.

Richardson, J.R., and T.T. Harris. 1995. Vegetation mapping and change detection in the Lake Okeechobee marsh ecosystem. Archiv für Hydrobiologie, Advances in Limnology 45:17-39.

Robblee, M.B., T.R. Barber, P.R. Carlson, M.J. Durako, J.W. Fourqurean, L.K. Muehlstein, D. Porter, L.A. Yarbro, R.T. Zieman, and J.C. Zieman. 1991. Mass mortality of the tropical seagrass *Thalassia testudinum* in Florida Bay (USA). Marine Ecology Progress Series 71:297-299.

Rogers, M.W. and M.S. Allen. 2008. Hurricane impacts to Lake Okeechobee: Altered hydrology creates difficult management tradeoffs. Fisheries 33:11-17.

Rosen, B.H., K.A. Loftin, J.L. Graham, K.N. Stahlhut, J.M. Riley, B.D. Johnston, and S. Senegal. 2018. Understanding the effect of salinity tolerance on cyanobacteria associated with a harmful algal bloom in Lake Okeechobee, Florida: U.S. Geological Survey Scientific Investigations Report 2018–5092, Ed. U.S.G. Survey, 32 p. Reston, VA: United States Geological Survey.

Rudnick, D.T., Z. Chen, D.L. Childers, J.N. Boyer, and T.D. III Fontaine. 1999. Phosphorus and nitrogen inputs to Florida Bay: the importance of the Everglades watershed. Estuaries 22(2):398-416.

Runge, M.C., C.A. Sanders-Reed, C.A. Langtimm, J.A. Hostetler, J. Martin, C.J. Deutsch, L.I. Ward-Geiger, and G.L. Mahon. 2017. Status and threats analysis for the Florida manatee (Trichechus manatus latirostris), 2016: U.S. Geological Survey Scientific Investigation Report 2017–5030, 40. Reston, VA: United States Geological Survey.

Ryther, J.H., and W.M. Dunstan. 1971. Nitrogen, phosphorus and eutrophication in the coastal marine environment. Science 171:1008-1013.

Saunders, C.J. and S. Newman. 2017. Triggers Guiding Year-Round DPM Operations of the S152 based on Statistical Analyses of Canal Water TP Variation. Supplemental Environmental Assessment and Proposed Finding of No Significant Impact Installation, Testing And Monitoring Of A Physical Model For The Water Conservation Area 3 Decompartmentalization And Sheetflow Enhancement Project: Phase 2, Appendix B.

Scheffer, M. 1989. Alternative stable states in eutrophic shallow freshwater systems: a minimal model. Hydrobiological Bulletin 23:73-85.

Scheffer, M., S.H. Hosper, M.L. Meijer, B. Moss, and E. Jeppesen. 1993. Alternative equilibria in shallow lakes. Trends in Ecology & Evolution 8(8):275-279.

Scheffer, M., S. Carpenter, J. Foley, C. Folke and B. Walker. 2001. Catastrophic shifts in ecosystems. Nature 413:591-596.

Schelske, C.L., H.J. Carrick, and F.J. Aldridge. 1995. Can wind-induced resuspension of meroplankton affect phytoplankton dynamics? Journal of the North American Benthological Society 14:616-630.

Schelske, C.L., E.F. Lowe, W.F. Kenney, L.E. Battoe, M. Brenner, and M.F. Coveney. 2010. How anthropogenic darkening of Lake Apopka induced benthic light limitation and forced the shift from macrophyte to phytoplankton dominance. Limnology and Oceanography 55:1201-1212.

Sellers, M.A., and J.G. Stanley. 1984. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (North Atlantic) - American oyster, Ed. US Fish and Wildlife Service.

SFWMD. 2002. Technical documentation to support development of minimum flows for the St. Lucie River and Estuary. West Palm Beach. FL: South Florida Water Management District.

SFWMD. 2006. Restoration plan for the northwest fork of the Loxahatchee River. South Florida Water Management District, West Palm Beach, Florida.

SFWMD. 2008. Lake Okeechobee Watershed Construction Project: Phase II Technical Plan. South Florida Water Management District, West Palm Beach, Florida.

SFWMD. 2008. South Florida environmental report. South Florida Water Management District, West Palm Beach, Florida.

SFWMD. 2009. South Florida environmental report. South Florida Water Management District, West Palm Beach, Florida.

SFWMD. 2010. Final Adaptive Protocols of Lake Okeechobee Operations, September 6. South Florida Water Management District developed in cooperation with USACE and FDEP.

SFWMD. 2014. 2014 South Florida Environmental Report. Volume 1. The South Florida Environment. South Florida Water Management District, West Palm Beach, FL. Retrieved from: http://www.sfwmd.gov/portal/page/portal/pg_grp_sfwmd_sfer/portlet_prevreport/2014_sfer/v1/vol1_table_of_contents.html

SFWMD. 2018. Technical Document to Support Reevaluation of the Minimum Flow Criteria for the Caloosahatchee River Estuary. January 30. South Florida Water Management District, West Palm Beach, Florida.

SFWMD. 2018. Water Flow and Nutrient Loads to Lake Okeechobee and the St. Lucie and Caloosahatchee Estuaries in Water Years 2014-2018. Draft Report. South Florida Water Management District, West Palm Beach, Florida.

SFWMD. 2019. 2019 South Florida Environmental Report. Volume 1. The South Florida Environment. South Florida Water Management District, West Palm Beach, FL. Retrieved from: https://apps.sfwmd.gov/sfwmd/SFER/2019_sfer_final/v1/chapters/v1_ch1.pdf

Shumway, E.E. 1996. Natural environmental factors. In: V.S. Kennedy, R.I.E. Newell, and A.F Eble (Eds.), The Eastern Oyster *Crassostrea virginica* (p. 467-513). College Park: Maryland Sea Grant College.

Sime, P. 2005. St. Lucie Estuary and Indian River Lagoon conceptual ecological model. Wetlands 25:898-907.

Simpfendorfer, C.A., B.G. Yeiser, T.R. Wiley, G.R. Poulakis, P.W. Stevens, and M.R. Heupel. 2011. Environmental influences on the spatial ecology of juvenile smalltooth sawfish (*Pristis pectinata*): Results from acoustic monitoring. Plos One 6(2):12.

SJRWMD and SFWMD. 1994. Surface water improvement and management plan for the Indian River Lagoon. St. Johns River Water Management District, Palatka, Florida.

Sklar, F. H., et al. (2005). "The ecological-societal underpinnings of Everglades restoration." Frontiers in Ecology and the Environment **3**(3): 161-169.

Smith, D.H., and M. Smart. 2005. Influence of water lake level on persistence of giant bulrush communities in Lake Okeechobee, Florida. Report to the South Florida Water Management District, 9 p.

Smith, J.P., and M.W. Collopy. 1995. Colony turnover, nest success and productivity, and causes of nest failure among wading birds (*Ciconiiformes*) at Lake Okeechobee, Florida (1989-2002). Archiv für Hydrobiologie, Advances in Limnology 45:287-316.

Smith, J.P., J.R. Richardson, and M.W. Collopy. 1995. Foraging habitat selection among wading birds (*Ciconiiformes*) at Lake Okeechobee, Florida, in relation to hydrology and vegetative cover. Archiv für Hydrobiologie, Advances in Limnology 45:247-285.

Smith, S.V. 1984. Phosphorus versus nitrogen limitation in the marine environment. Limnology and Oceanography 29(6):1149-1160.

Smith, T.J., III, J.H. Hudson, M.B. Robblee, G.V.N. Powell, and P.J. Isdale. 1989. Freshwater flow from the Everglades to Florida Bay: a historical reconstruction based on fluorescent banding in the coral *Solenastrea bournoni*. Bulletin of Marine Science 44(1):274-282.

Steinman, A.D., K.E. Havens, A.J. Rodusky, B. Sharfstein, R.T. James, and M.C. Harwell. 2002. The influence of environmental variables and a managed water recession on the growth of charophytes in a large subtropical lake. Aquatic Botany 72:297-313.

Tian, Y. and M. T. Huang (2019). "An Integrated Web-Based System for the Monitoring and Forecasting of Coastal Harmful Algae Blooms: Application to Shenzhen City, China." Journal of Marine Science and Engineering 7(9): 17.

Trimble, P., and J. Marban. 1988. Preliminary Evaluation of the Lake Okeechobee Regulation Schedule. Technical Publication 88-5. South Florida Water Management District.

URS Greiner Woodward Clyde. 1999. Distribution of oysters and submerged aquatic vegetation in the St. Lucie estuary. Final report to the South Florida Water Management District. South Florida Water Management District, West Palm Beach, Florida.

USACE and SFWMD. 2004. Central and southern Florida project Indian River Lagoon south final integrated project implementation report and environmental impact statement. U.S. Army Corps of Engineers, Jacksonville, Florida.

USACE. 2007. Final Supplemental Environmental Impact Statement Including Appendices A through G: Lake Okeechobee Regulation Schedule. U.S. Army Corps of Engineers, Jacksonville District, Jacksonville, FL.

USACE. 2008. Central and South Florida Project, Water Control Plan for Lake Okeechobee and Everglades Agricultural Areas, March 2008. Appendix I.

USACE, and SFWMD. 2010. Central and Southern Florida Project Caloosahatchee River (C-43) West Basin storage reservoir project, Final integrated project implementation report and final environmental impact statement, Ed. Jacksonville District and South Florida Water Management District U.S. Army Corps of Engineers.

USACE. 2016. South Florida Ecosystem Restoration (SFER) Program Overview. https://www.saj.usace.army.mil/Portals/44/docs/Environmental/Everglades%20Restoration%20Overview%20Placemat_May2016_web.pdf

Van Horn, S. 2019. St. Lucie and Caloosahatchee watersheds: focus on water quality. Presentation to the South Florida Water Management District Governing Board.

Van, T.K., W.T. Haller, and G. Bowes. 1976. Comparison of the photosynthetic characteristics of three submersed macrophytes. Plant Physiology 58:761-768.

Vargo, G.A., C.A. Heil, K.A. Fanning, L.K. Dixon, M.B. Neely, K. Lester, and D. Ault, et al. 2008. Nutrient availability in support of *Karenia brevis* blooms on the central West Florida Shelf: What keeps *Karenia* blooming? Continental Shelf Research 28(1):73-98.

Volety, A.K., M. Savarese, S.G. Tolley, W.S. Arnold, P. Sime, P. Goodman, R.H. Chamberlain, and P.H. Doering. 2009. Eastern oysters (*Crassostrea virginica*) as an indicator for restoration of Everglades Ecosystems. Ecological Indicators 9:S120-S136. doi:10.1016/j.ecolind.2008.06.005.

Wachnicka, A., and G.L. Wingard. 2015. Biological indicators of changes in water quality and habitats of the coastal and estuarine areas of the Greater Everglades ecosystem. In: A.D. Gottlieb, K. Jayachandrhan, and A. Ogram (Eds.), Microbiology of the Everglades Ecosystem (p. 218-240). Boca Raton, FL: CRC Press.

Walker, W.W. Jr. and K.E. Havens. 1995. Relating algal bloom frequencies to phosphorus concentrations in Lake Okeechobee. Lake and Reservoir Management 11:77-83.

Welch, Z., J. Zhang, and P. Jones. 2018. Draft 2019 South Florida Environmental Report – Volume I, Chapter 8B: Lake Okeechobee Watershed Annual Report. https://apps.sfwmd.gov/sfwmd/SFER/2019_sfer_draft/v1/chapters/v1_ch8b.pdf

Wiginton, J.R., and C. McMillan. 1979. Chlorophyll composition under controlled light conditions as related to the distribution of seagrasses in Texas and the U.S Virgin Islands. Aquatic Botany 6:171-184.

Will, L.E. 1961 [1978]. Okeechobee Hurricane: Killer Storms in the Everglades. The Glades Historical Society, Belle Glade, FL. 204 p.

Wingard, G.L., T.C. Cronin, G.S. Dwyer, S.E. Ishman, D.A. Willard, C.W. Holmes, and C.E. Bernhardt, et al. 2003. Ecosystem history of southern and central Biscayne Bay: summary report on sediment core analysis. Open File Report 03-375, Ed. U. S. Geological Survey.

Wingard, G.L., T.M. Cronin, C.W. Holmes, D.A. Willard, G.S. Dwyer, S.E. Ishman, W. Orem et al. 2004. Ecosystem history of southern and central Biscayne Bay: summary report on sediment core analyses. Open File Report 2004-1312, Ed. U.S. Geological Survey. https://doi.org/10.3133/ofr03375

Wingard, G.L., C.E. Bernhardt, and A.H. Wachnicka. 2017. The role of paleoecology in restoration and resource management—the past as a guide to future decision-making: review and example from the greater Everglades ecosystem, USA. Frontiers in Ecology and Evolution 5(11):1-24.

Yan, Y.Y., and R.T. James. 2012. Spatial modeling of mud thickness and mud weights (1988-2006), Lake Okeechobee. The Florida Geographer 43:17-36.

Yang, Y.E., Z.L. He, Y.J. Lin, E.J. Phlips, J.Y. Yang, G.C. Chen, P.J. Stoffella, and C.A. Powell. 2008. Temporal and spatial variations of nutrients in the Ten Mile Creek of South Florida, USA and effects on phytoplankton biomass. Journal of Environmental Monitoring 10(4):508-516.

Zieman, J.C. 1982. The ecology of the seagrasses of south Florida: a community profile. Washington, DC: U.S. Fish and Wildlife Service.