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PROGRESS TOWARD RESTORING THE EVERGLADES

The Eighth Biennial Review - 2020

Committee on Independent Scientific Review of Everglades Restoration Progress

Water Science and Technology Board

Division on Earth and Life Studies

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Reviewer Acknowledgment

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Although these reviewers provided many constructive comments and suggestions, they were not asked to endorse the conclusions and recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by **Kenneth W. Potter**, University of Wisconsin and **Bonnie McCay**, Rutgers, The State University of New Jersey. Appointed by the National Academies, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments received full consideration. Responsibility for the final content of this report rests entirely with the authoring committee and the National Academies.

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Dedication

This report is dedicated to the memory of two long-time supporters of the Everglades and its restoration, Drs. Karl Havens and William (Will) Graf. Karl was a member of the faculty of the University of Florida and the director of the Florida Sea Grant program. He was a member of the National Academies Committee on Independent Scientific Review of Everglades Restoration Progress (CISRERP), participating in committees in 2014 and 2016. Karl was an internationally recognized scholar on the response of freshwater and coastal ecosystems to human disturbances, including excess nutrients and climate change. He had considerable research interests and experience in Lake Okeechobee and Everglades restoration, which this committee put to good use. Karl was passionate in his personal and professional interests and always generous with this time and energy. Karl was an ardent and talented photographer and a great resource for interesting eateries in South Florida.

Will Graf was a Foundation University Professor Emeritus at the University of South Carolina. He served on CISRERP committees from 2004 to 2016, including as chair for the second biennial review (NRC, 2008). He also served on two prior National Academies Everglades committees from 2002 to 2004. Will had a long and distinguished career in geography, focusing on the geomorphology and hydrology of rivers, and the intersection of science and policy for public lands and waters. Will was generous in professional service, and he chaired or served on more than 20 committees of the National Academies, serving continuously on at least one committee (sometimes more) for 30 years. He had many interests, including hiking, kayaking, and traveling, and he delighted in sharing these passions with other committee members by organizing bicycling adventures in Newport Beach and a subgroup trip to Picayune Strand. The committee fondly remembers Will's train whistle calling committee meetings to order and his relentless enthusiasm for the application of Everglades restoration science.

Karl and Will were tremendous colleagues and great friends. They will be missed.

Preface

The Everglades is a wondrous and unique landscape. This vast wetland drains a complex of sawgrass marshes and sloughs, hardwood hammocks, pinelands, and cypress swamps before discharging into its surrounding estuaries, including the St. Lucie Estuary, the Caloosahatchee Estuary, Biscayne Bay, and Florida Bay. The Everglades is also surrounded by ever-increasing urban development. Although there is an inherent tension between the built and natural environment, a fully functioning Everglades is critical to many ecosystem services that benefit the ever-increasing population of South Florida, including drinking water supply; mitigation against sea-level rise and storm surges; and healthy, productive and diverse wildlife and fisheries, among many others. Unfortunately, drainage and development compromised the form and function of the Everglades and continue to impair the quantity and quality of water. Recent observations show that the Everglades are also increasingly challenged by changing climate. Sea-level rise, erratic and extreme weather, and harmful algal blooms are all manifestations of climate change and have focused public attention on the critical need to restore and protect the natural environment of South Florida.

Recognizing the consequences of the long-term degradation of the South Florida landscape, in 1999 the federal government partnered with the State of Florida to initiate the Comprehensive Everglades Restoration Plan (CERP) to maintain and improve the ecosystem's structure and function. In establishing the CERP, Congress also requested that an independent scientific review be conducted on progress toward restoration with biennial reports. The National Academies formed the Committee on Independent Scientific Review of Everglades Restoration Progress (CISRERP) in 2004. This report is the eighth in the series.

This report period coincides with a particularly exciting period for the CERP. Twenty years in, the restoration efforts are, at last, seeing the completion and operation of some projects and progress in others. This transition from planning projects to beginning of their operation, integration, and optimization is rewarding for the many people and groups who have worked long and hard on Everglades restoration. This pivot toward project operation represents an opportunity to learn about the first stages of ecosystem response to restoration and to use this information to inform and guide future restoration efforts.

The CISRERP is comprised of scientists, social scientists, and engineers with a range of relevant expertise and experience in the environmental sciences, hydrology, wetland and estuarine science, systems engineering, statistics, modeling, project and program administration, law, economics, and public policy. Some committee members have experience in past CISRERP reviews or have relevant research experience working on the Everglades. Other committee members are less familiar with this complex and important system. This span of experience is healthy and brings a range of perspectives to the issues and activities we considered. The full committee met on four occasions in Florida and twice virtually over a 12-month period. We reviewed reports and published literature, heard oral presentations, and had discussions with federal, state. and tribal personnel, academic scientists, representatives of nongovernmental organizations and interest groups, and the public. I am humbled and honored to work with such a distinguished and dedicated group. The CISRERP members are highly accomplished and have worked diligently and effectively as a team to produce this report. I have been impressed with the careful analysis, ideas, time committed, and thoughtful suggestions by committee members in reviewing materials and developing the report. This report represents a consensus of the committee on the restoration progress and challenges anticipated in future restoration not only from the perspective of the most recent 2-year period, but also more broadly since the CERP was initiated 20 years ago.

The committee is indebted to many individuals for supplying information and resources that have been critical to our review. In particular, the committee's technical liaisons—Glenn Landers (USACE), Eva Velez (USACE), Nafeeza Hooseinny (SFWMD), and Robert Johnson (Department of the Interior)—

greatly facilitated our work by effectively responding to frequent requests for information and providing access to agency resources and expertise. The committee is appreciative of the efforts of numerous people who readily provided valuable insights and knowledge of the Everglades ecosystem and its restoration through presentations, conversations, terrific field trips, and public comments (see Acknowledgments).

The committee has been extremely fortunate to work with gifted staff from the National Academies to help us meet our charge. Stephanie Johnson has been stellar as project officer of eight CISRERP committees for the National Academies. The CERP is a remarkably challenging and interesting program entailing a complex biophysical system, many interconnected restoration projects, a number of federal, state, and tribal agencies who work together to accomplish the restoration, and stakeholders who are passionate about the Everglades but at times have conflicting ideas and interests. Stephanie's intellect, experience, and tenacity have been essential to help the committee navigate through the complexity in order to address the issues facing CERP. Her perseverance and leadership have been critical in the development of this report. We were fortunate to have the services of Brendan McGovern to support the logistical needs of the committee and provide sage advice on local restaurants for memorable and productive dinners after committee meetings and field trips. Unfortunately, Brendan left the National Academies before the committee's work was complete. His positive outlook, hard work, and stories have been missed. Fortunately, Brendan was replaced by Eric Edkin. Eric's technical mastery was invaluable to the committee, particularly when it was necessary to transition to virtual meetings. Without these capable staff, the committee would have difficulty meeting the challenge of this review and report.

Charles Driscoll, *Chair*
Committee on Independent Scientific
Review of Everglades Restoration Progress

Contents

APPENDIXES

Acronyms

AF	acre-feet
ASR	aquifer storage and recovery
BBCW	Biscayne Bay Coastal Wetlands
BBSEER	Biscayne Bay and Southeastern Everglades Ecosystem Restoration
BBSM	Biscayne Bay Simulation Model
BMP	best management practice
BOD	biochemical oxygen demand
C&SF	Central and Southern Florida
CEPP	Central Everglades Planning Project
CERP	Comprehensive Everglades Restoration Plan
cfs	cubic feet per second
CHNEP	Coastal & Heartland National Estuary Partnership
CISRERP	Committee on Independent Scientific Review of Everglades Restoration Progress
COP	Combined Operational Plan
CROGEE	Committee on the Restoration of the Greater Everglades Ecosystem
CSSS	Cape Sable seaside sparrow
DOI	U.S. Department of the Interior
EAA	Everglades Agricultural Area
ENP	Everglades National Park
EPA	U.S. Environmental Protection Agency
ERTP	Everglades Restoration Transition Plan
FDEP	Florida Department of Environmental Protection
FEB	flow equalization basin
FWS	U.S. Fish and Wildlife Service
FY	fiscal year
HAB	harmful algal bloom
HSI	habitat suitability index
IDS	Integrated Delivery Schedule
IOP	Interim Operational Plan
IRL-S	Indian River Lagoon-South
LNWR	Loxahatchee National Wildlife Refuge
LOWRP	Lake Okeechobee Watershed Restoration Project
LTER	Long-Term Ecological Research
MAP	monitoring and assessment plan

NASEM	National Academies of Sciences, Engineering, and Medicine
NCEAS	National Center for Ecological Analysis and Synthesis
NGVD	National Geodetic Vertical Datum
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NPS	National Park Service
NRC	National Research Council
PACR	Post Authorization Change Report
PPA	project partnership agreement
ppb	parts per billion
ppt	parts per thousand
PSU	practical salinity unit
QAOT	Quality Assurance Oversight Team
RECOVER	REstoration, COordination, and VERification
RPA	reasonable and prudent alternative
RSM	Regional Simulation Model
SAV	submerged aquatic vegetation
SEACOM	Florida Bay Seagrass Community Model
SESYNC	National Socio-Environmental Synthesis Center
SFERTF	South Florida Ecosystem Restoration Task Force
SFWMD	South Florida Water Management District
SFWMM	South Florida Water Management Model
SSR	System Status Report
STA	stormwater treatment area
TMDL	total maximum daily load
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
WAI	wetland affinity index
WCA	Water Conservation Area
WERP	Western Everglades Restoration Project
WQBEL	water quality–based effluent limit
WRDA	Water Resources Development Act
WSE	Water Supply and Environment
WY	water year (May 1 to April 30)

Summary

During the past century, the Everglades, one of the world's treasured ecosystems, has been dramatically altered by drainage and water management infrastructure to improve flood management, urban water supply, and agricultural production. The remnants of the original Everglades now compete for water with urban and agricultural interests and are impaired by contaminated runoff from these two sectors. The Comprehensive Everglades Restoration Plan (CERP), a joint effort launched by the state and the federal government in 2000, seeks to reverse the decline of the ecosystem. The multibillion-dollar project was originally envisioned as a 30- to 40-year effort to achieve ecological restoration by reestablishing the natural hydrologic characteristics of the Everglades, where feasible, and to create a water system that serves the needs of both the natural and the human systems of South Florida.

The National Academies of Sciences, Engineering, and Medicine established the Committee on Independent Scientific Review of Everglades Restoration Progress in 2004 in response to a request from the U.S. Army Corps of Engineers, with support from the South Florida Water Management District (SFWMD) and the U.S. Department of the Interior, based on Congress's mandate in the Water Resources Development Act of 2000. The committee is charged to submit biennial reports that review the CERP's progress in restoring the natural ecosystem. This is the committee's eighth report. Each report provides an update on progress toward natural system restoration during the previous 2 years, describes substantive accomplishments (Chapter 3), and reviews developments in research, monitoring, and assessment that inform restoration decision making (Chapters 3 and 6). The committee also identifies issues for in-depth evaluation given new CERP program developments, policy initiatives, or improvements in scientific knowledge that have implications for restoration progress (see Chapter 1 for the committee's full statement of task). For the 2020 report, the committee reviewed the recently developed Combined Operational Plan (COP), which is a prerequisite for CERP progress in the central Everglades (Chapter 4), and examined issues facing the northern and southern estuaries, including priorities for science to support restoration decision making (Chapter 5). Additionally, the committee examined the capacity of CERP monitoring, modeling, and synthesis to support decision makers (Chapter 6).

OVERALL EVALUATION OF PROGRESS AND CHALLENGES

Over the past 2 years, CERP implementation has proceeded at a steady pace, with construction ongoing on six major projects (Figure S-1), supported by historic levels of funding from both state and federal partner agencies. After more than two decades of work to complete two major non-CERP projects, the Combined Operational Plan has been completed, delivering significant benefits to Water Conservation Area 3 and Everglades National Park, setting the stage for restoration in the central Everglades and enabling the opportunity to learn about system response to restoration and enhance future CERP benefits. At the same time, the South Florida estuaries remain under threat from habitat degradation, water quality issues, and harmful algal blooms; some of these threats fall outside of the direct influence of CERP and may limit the capacity to achieve CERP goals.

With several projects nearing completion, the CERP is now pivoting from a focus primarily on project planning and construction toward an expanding emphasis on operational decisions, evaluating restoration success, adaptive management, and learning. This transition requires a strong organizational foundation for science, systematic monitoring and assessment, effective communication, and new strategies to support decision making. From this analysis, key principles emerge that are relevant across different projects and regional contexts. First, effective monitoring and ongoing data analysis are critical to support assessments of restoration progress, learning, and adaptive management. Synthesis, improved integration of modeling and monitoring, and enhanced applications of modeling tools can be used to turn available information into better understanding to evaluate tradeoffs and strengthen decision making. Finally, strong science leadership and appropriate staffing are key elements of an organizational infrastructure to maximize learning and to support more nimble decision making. Investments in the science and decision-making infrastructure for the CERP would improve the value of information developed through monitoring, modeling, and synthesis and lead to more effective restoration outcomes.

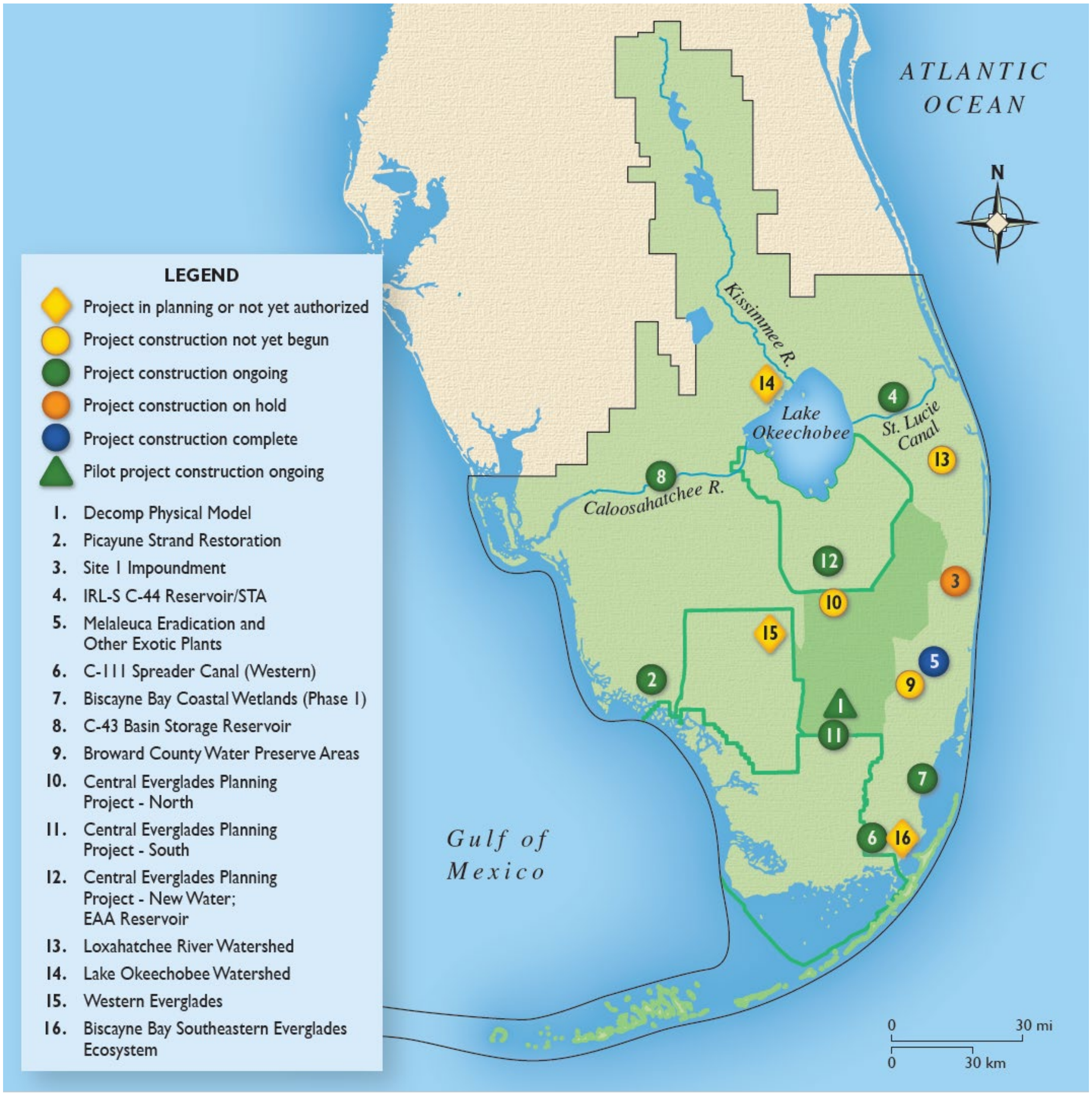


FIGURE S-1 Locations and status of CERP projects. SOURCE: International Mapping Associates. Reprinted with permission; copyright 2021, International Mapping Associates.

RESTORATION PROGRESS

In Chapter 3, the committee outlines the major accomplishments of restoration, with an emphasis on natural system restoration progress from the CERP, and discusses issues that may affect progress.

State and federal funding for the CERP has increased significantly in recent years, which expedites the pace of project construction. Following a period of historically low state and federal funding for the CERP (2012-2016), state funding for the CERP has approximately doubled to more than $200 million per year. With federal CERP funding of $247 million in FY 2020, CERP funding has exceeded the original vision of $200 million per year from both the state and the federal government for the first time since the program's inception, and similar funding levels are anticipated in FY 2021. With this increased funding, CERP projects can be completed more quickly, resulting in faster restoration benefits and potentially mitigating ongoing ecosystem degradation.

The 2019 Integrated Delivery Schedule (IDS) does not effectively communicate likely restoration schedules and priorities consistent with realistic funding constraints. The Integrated Delivery Schedule is a communication tool across agencies that provides information to guide project sequencing and budgeting. The anticipated future progress of CERP projects and the relationships among other large non-CERP restoration projects are depicted in the IDS. The 2019 IDS is based on the fastest possible construction schedule, given project dependencies, regardless of budget; the IDS assumes an average funding of more than $800 million per year for the first 5 years (nearly double the record budget in FY 2020). These assumptions may be acceptable for the purpose of explaining the benefits of increased funding, but they fail to support the difficult decisions that must be made when future funding is inadequate to meet these optimistic projections. CERP planners, in some simple alternative scenarios, assume that reduced funding simply stretches the timeline of the IDS proportionally. However, an optimal project prioritization is likely to be time dependent. In light of ongoing degradation of the system and peat collapse in the southern Everglades, it is probably unwise for all projects to be delayed equally with reduced funding. Rather, some projects should be prioritized based on project benefits in relation to ongoing system degradation. Uncertainty of funding (which occurs on a regular basis) necessitates evaluation of realistic and alternative levels of funding with consideration of the many time-dependent factors that may affect an optimal project prioritization. Development of the IDS could serve as a means to debate these challenging decisions with the multiple CERP agencies and stakeholders, as well as communicate the effects of schedule changes on the nature and timing of anticipated ecosystem benefits in the context of current ecosystem trends and ongoing pressures such as sea-level rise and harmful algal blooms.

Signs of restoration progress are evident from three CERP project increments operating to date, but limitations in monitoring, analysis, and communication of results have impeded quantitative assessment and communication of restoration benefits. Increments of the Picayune Strand and Biscayne Bay Coastal Wetlands (Phase 1) projects and nearly all of the envisioned C-111 Spreader Canal (Western) project have been operating for years, providing an important opportunity to learn from those results and communicate those incremental benefits to the public. Results from monitoring in Biscayne Bay Coastal Wetlands and Picayune Strand show positive trends and qualitative evidence of effects from implementation. Operations have been refined in the Biscayne Bay Coastal Wetlands project to improve restoration outcomes (although some benefits remain limited by lack of available freshwater). Assessments of restoration progress continue to be stymied by a lack of systematic analyses of quantitative results from early indicators of restoration relative to expected outcomes. Without this information, it is difficult to assess and communicate progress. This limitation applies to all three projects in some dimension, but is most evident in the C-111 Spreader Canal and Picayune Strand projects, and improvements are needed. Understanding the challenges and opportunities for improved monitoring will lead to better restoration assessment.

Important opportunities for learning from monitoring at Picayune Strand are being missed that could inform current and future project management decisions across CERP and non-CERP agencies. Understanding the response of vegetation and fauna to restoration at Picayune Strand is hindered by invasive species and fire management. Widespread drainage of the area allowed invasive species to become established. Project managers should revisit the project goals and expectations, potentially shifting the ecological objectives toward improving conditions for desirable species and increasing resilience across the region to respond to climate change. Improved coordination across CERP and non-CERP agencies regarding fire management is needed. The monitoring plan should also be redesigned to support adaptive management of the project. An acknowledgment that hydrologic restoration is unlikely to replicate predrainage ecology could help agencies prioritize additional management actions, including fire management, necessary to achieve these revised goals.

Stormwater treatment areas (STAs) have been an effective approach to mitigate total phosphorus inputs to the Everglades Protection Area, but recent high concentrations in STA-2 effluent, several years after implementation of Restoration Strategies features for the central flowway, raise concerns. The SFWMD 2018 Science Plan provides recommendations for evaluating factors to improve the performance of STAs that could be helpful in achieving lower effluent concentrations of total phosphorus and guide future operations. The SFWMD is planning to complete Restoration Strategies by 2025, and has until 2027 to demonstrate compliance. However, intensive efforts now to analyze and optimize performance and address shortfalls could help avoid delays in meeting the water quality criteria and delivering new water to the central Everglades. With heightened concerns about elevated nutrient loading and harmful algal blooms in the northern estuaries, the state is increasingly interested in water quality management of contaminants beyond phosphorus, especially for nitrogen. Research to improve understanding of nitrogen retention and loss in STAs and the potential to enhance nitrogen removal would inform decisions on the management of harmful algal blooms.

Phased implementation of major features of the Lake Okeechobee Watershed Restoration Project (LOWRP) will help accommodate the numerous uncertainties associated with aquifer storage and recovery (ASR), a technology that remains unproven at the proposed scale of deployment. The objectives of the LOWRP include reducing damaging discharges to the northern estuaries and improving lake levels in Lake Okeechobee. The tentatively selected plan proposes reduced above-ground water storage relative to the original CERP vision with the bulk of water storage provided by ASR wells. To address critical unknowns while moving forward with restoration, installation should proceed in increments of two to five ASR wells with postinstallation monitoring conducted to address outstanding questions related to the quality of recharged and recovered waters, ecological effects, and recovery efficiencies. Because above-ground storage provided by the wetland attenuation feature is small and its benefits are largely linked to the performance of ASR, the recently proposed schedule that postpones construction of the wetland attenuation feature until the ASR uncertainties are resolved is appropriate. Prior to construction, the contributions of the wetland attenuation feature to LOWRP's objectives of regulating lake water levels and estuary discharges should also be clarified and considered in the context of its cost.

The Everglades remain vulnerable overall to continuing degradation. The Restoration, Coordination, and Verification (RECOVER) 2019 System Status Report noted the dire condition of the Everglades ecosystem, with a "fair" rating of conditions systemwide and "poor" conditions in the Southern Coastal Systems. Overall, the CERP projects operating to date have been limited and are disconnected on the landscape, leading to limited detectable responses of restoration at a systems scale. However, with several large reservoirs under construction in the northern Everglades and the Combined Operational Plan in place in the southern part of the ecosystem, substantial restoration benefits are expected in the years ahead.

The System Status Report provides a useful compilation of data, but the lack of reporting of long-term trends and influencing factors limits its value to adaptive management and operational decision making. In the 2019 System Status Report, RECOVER compiles and presents a substantial amount of data to document the status and trends of the Everglades restoration for the period 2012-2017. Rigorous long-term trend analysis was not completed, making it more difficult to assess restoration progress and the causes of any observed changes. Synthesis of the findings of more rigorous multivariate analyses are needed in future system status reports to effectively leverage the results and develop improved systems-level understanding that can be used to inform future decisions. The Everglades Report Card, included as a stand-alone graphical summary of ecological conditions, represents a positive step in public communications, although methodological issues in some of the scoring approaches will need to be remedied in future reports.

Combined Operational Plan (COP)

In Chapter 4, the committee reviews the COP, a new, comprehensive, integrated water control plan that defines the operations of the recently completed Modified Water Deliveries to Everglades National Park (Mod Waters) and C-111 South Dade projects. These non-CERP projects are called foundation projects because the CERP builds upon the benefits that they provide.

The COP is expected to provide substantial hydrologic and ecological benefits to Water Conservation Area (WCA) 3A and Everglades National Park, although the full benefits from the Mod Waters and C-111 South Dade projects afforded by the plan have not been quantified. The benefits of the preferred plan are documented relative to a baseline condition of field test Increment 1.2, which itself provides substantial benefits above the prior regional operational plan, using the Mod Waters and C-111 South Dade infrastructure. The benefits provided by Increment 1.2 have not been fully quantified but are estimated to be as large as those documented for the COP. Quantifying the full benefits of the Mod Waters and C-111 South Dade projects would help stakeholders understand the expected effects of these public investments. The COP preferred alternative is projected to increase annual flow into Everglades National Park by 28 percent (relative to the Increment 1.2 baseline) and increase the percentage of flow into Northeast Shark Slough from 58 to 77 percent, more closely approximating historic flow patterns and rehydrating its wetlands. The plan is also projected to reduce tree island inundation in WCA-3 by 24 percent and provide an additional 36,000 acre-feet per year to eastern Florida Bay. Habitat conditions for the endangered Cape Sable seaside sparrow are projected to improve in some areas and be negatively impacted in others. To avoid constraints on operations imposed to protect the Cape Sable seaside sparrow that have limited the restoration success of previous water management plans, additional mitigation strategies may be needed to ensure that sparrows occupy new habitat created by the COP to offset anticipated losses of current sparrow habitat.

Flood risk management is the primary constraint to increased restoration benefits from the COP and is likely to pose a major limitation to increased CERP flows in the central Everglades unless additional flood risk mitigation or seepage control efforts are made. Despite large investments in land acquisition and flood mitigation projects in the 8.5 square-mile area, a residential area located west of the eastern protective levee, flood risk management in this area continues to limit restoration benefits from the COP. Although Mod Waters infrastructure was designed for a maximum L-29 canal stage of 8.5 feet National Geodetic Vertical Datum of 1929 (NGVD), Tamiami Trail roadway protection and flood risk management requirements for the 8.5 square-mile area currently limit the number of days the L-29 canal can be operated at a stage above 8.3 feet NGVD. CERP projects and Tamiami Trail Next Steps are designed for a stage of 9.7 feet NVGD in the L-29 canal. Without additional flood mitigation projects or seepage control efforts, flood risk management on the eastern edge of Everglades National Park could greatly limit the benefits of future CERP projects to increase flow to the central Everglades. Efforts to expedite additional seepage management features or other flood risk management strategies will be critical to providing new water to the remnant Everglades.

The process to develop the COP was systematic and comprehensive, but three considerations could improve future planning efforts: transparency in multiobjective trade-off analysis, characterization of model uncertainty, and evaluation of performance under future conditions. The COP process involved field testing and rigorous model analyses to develop and assess alternatives using performance measures related to ecological benefits and flood risk management, covering a large area from the water conservation areas to Florida Bay. However, trade-offs among various objectives and other "planning considerations and concerns," such as flood risk management, were neither transparent nor well documented, leaving stakeholders unclear if ecological objectives were compromised for other considerations. Lack of characterization of model uncertainty limits the potential application of adaptive management, because when observations fall outside of model projections, it is unclear whether this is due to model error or if the system is not responding as expected. Finally, analysis of the COP under a range of possible future conditions, rather than a single historical period, would provide a more realistic estimate of the likely future performance.

The COP offers a remarkable opportunity to learn about restoration, inform the design and operation of CERP projects, and increase the benefits of the COP through adaptive management. The COP marks a pivot from project development to the task of optimizing the performance of new features to achieve ecological objectives under competing interests and uncertain future conditions. Effective management of the system will require assimilation of observations and expectations, and adaptive responses to new information. The COP Adaptive Management and Monitoring Plan contributes to these needs. The plan was thoughtfully developed, used a logical approach to identify the highest priority uncertainties, and provided clear monitoring thresholds that trigger additional management actions. The plan provides a framework to ensure that benefits from restoration projects are realized and offers management actions to accommodate changes in the ambient environmental conditions. Sizable potential exists for COP monitoring and assessment to inform the CERP program more broadly. COP monitoring data can be used to examine deficiencies in model predictions and improve the predictive capacity of modeling tools. It can also be used to reveal gaps in understanding of the ecosystem and its response to restored hydrology that have systemwide applications, including beginning to test the fundamental assumption that “getting the water right” will result in the desired ecological restoration.

Scientific expertise is essential to support COP adaptive management, but lack of staff support and dedicated resources could limit the potential benefits of the adaptive management program. A structured process to facilitate the assessment of monitoring data and effective communication with decision makers has not been identified. It will be important that modeling tools and staff be made available to analyze and learn from the COP results and determine which outcomes represent significant deviations from expectations. Experienced staff with dedicated resources will be needed to provide routine multiagency review of assessment results and develop recommendations for management. Furthermore, the evidence-based decision making required to achieve COP objectives will benefit from programmatic linkages to share decision-relevant information from other CERP projects.

ESTUARIES

In light of recent events affecting the northern and southern estuaries, including seagrass die-off and harmful algal blooms, the committee examines the key issues facing Florida Bay, Biscayne Bay, the Caloosahatchee River Estuary, and the St. Lucie Estuary in Chapter 5.

The CERP will help address freshwater inflow concerns in all of the estuaries but it is only part of the solution. CERP ecological restoration goals, particularly in the northern estuaries and Biscayne Bay, cannot be met if water quality and associated algal blooms, which are outside of the direct purview of the CERP, are not addressed. CERP projects primarily aim to improve hydrologic and ecological conditions in the estuaries by enhancing the volume and timing of freshwater inflows, thereby bettering salinity conditions. However, additional hydrologic restoration beyond those planned to date for the CERP may be needed to meet stakeholder expectations for estuary recovery (e.g., reducing high-volume flows derived from local watersheds in the northern estuaries). Some CERP projects are expected to reduce nutrient loads, but the water quality components of CERP projects represent only minor aspects of the steps needed to meet water quality criteria in the estuaries. Requirements for compliance with the Clean Water Act to address pollution and water quality fall to the state and not to the CERP. Public expectations for improved estuarine conditions, such as healthy seagrass meadows, improved oyster habitat, and control of harmful algal blooms, extend beyond what the CERP alone can achieve and require both CERP actions and water quality improvements by non-CERP efforts. CERP planning has not rigorously considered the potential impacts of impaired water quality on its ecological goals. Understanding the collective impacts of hydrology and water quality in meeting restoration goals and stakeholder expectations is essential to support ongoing CERP and non-CERP management decisions. If the impacts of water quality are not well understood, CERP water management projects may be unfairly blamed for failing to meet expected outcomes.

CERP goals for the southern estuaries should be revisited and clarified in light of improved ecosystem understanding and modeling capabilities. Early formulations of the CERP had qualitative objectives for Biscayne and Florida Bays. Freshwater flow targets linked to spatially specific ecological goals were never developed for use in CERP planning because predrainage flows were not well understood and model predictions were poor along the coastal boundaries. For example, in Biscayne Bay, nearshore salinity goals were developed, but the absence of freshwater flow targets complicates an understanding of what is attainable. In Florida Bay, the authorized CERP and non-CERP projects do little to address the specific region where historic seagrass die-offs occurred. Analysis of ways to optimize CERP outcomes with available flows requires more spatially targeted goals for the region. Analysis of what can be achieved through the CERP is essential to manage stakeholder expectations and, if appropriate, motivate additional non-CERP efforts. Additionally, these analyses will facilitate evaluations of trade-offs in water use among other water users and other regions of the ecosystem.

Existing data and tools should be used to improve science support for decision making across the estuaries. The relevant agencies have a long history of monitoring, but existing modeling tools and data sets are underutilized. Models and monitoring data offer opportunities to rigorously examine restoration alternatives and constraints, better understand trade-offs, and develop management strategies to enhance restoration benefits.

CERP and non-CERP agencies will need an advanced set of predictive tools, developed and implemented through effective coordination among scientists and managers, to better support critical water management decisions ahead. High-priority science and modeling needs include

- Spatially explicit water quality models and a sustained program of observation and research to build toward a predictive harmful algal bloom modeling toolkit for the northern estuaries.
- Watershed loading and water quality models to predict effects of salinity, water quality, and light limitation on the viability of seagrass in Biscayne Bay.
- Spatially explicit and mechanistic biological models (e.g., seagrass, oyster), supported by appropriately scaled and sustained monitoring programs for the northern estuaries that can capture the quantitative basis for relationships between freshwater flows, water quality drivers, and biological outcomes of interest.
- Predictive tools to identify thresholds and tipping points in all the estuaries, such as the complex factors associated with algal blooms and seagrass die-off.
- A southern Everglades transition-zone observational and modeling program that supports project planning and can couple regional hydrologic models, including groundwater–surface water exchange, with spatially explicit estuarine hydrodynamic and salinity models.
- Integration of modeling and observations across the entire southern inland and coastal system to evaluate cross-project synergies and ecological responses (e.g., the ecological response of Biscayne Bay and Florida Bay to enhanced seepage management).

Clarity in critical future water management decisions can help prioritize additional research, monitoring, modeling, and synthesis efforts to better support CERP and non-CERP initiatives. Open communication and cooperation between subregion research, observational, and model development teams are needed to facilitate improved model coupling, accelerate knowledge gains, and allow models to collectively address trade-off decisions. Advancement in modeling could benefit from improved coordination across the estuaries to accelerate knowledge gains and allow broader regional approaches to address trade-offs in decisions.

Climate change and sea-level rise will have major effects on the estuaries, and those effects need to be better understood to inform management decisions and develop strategies that will

provide long-term restoration benefits. Terrestrial hydrologic monitoring, synthesis, and modeling in South Florida are relatively advanced, but this toolkit has not been applied to investigate the effects of climate change on the human and natural systems of the South Florida Everglades and associated estuaries. In the northern estuaries, estuarine hydrodynamic modeling is advanced, but in Florida Bay and Biscayne Bay, improvements to these modeling capabilities are needed. Improved modeling of coastal boundaries is required to understand the implications of sea level rise on groundwater and surface water inflows and saltwater intrusion. Additional research is needed to extend climate scenario predictions from effects on hydrology to effects on water quality and ecosystems. To ready the toolkit for this exercise, investments recommended above to make water quality and biological models increasingly mechanistic and spatially explicit will also serve to credibly predict impacts from climate change stressors. This information can then be used to examine the long-term performance of projects and identify possible adaptive management strategies or design alterations to increase ecosystem resilience.

SCIENCE SUPPORT FOR DECISION MAKING

The value of science—especially systems thinking and analysis—becomes even more important as the CERP pivots from a focus on planning and advancing individual projects to operations and management of the partially restored system. The transition from a focus almost exclusively on multiyear CERP planning efforts to providing support for ongoing adaptive management of numerous projects in parallel with ongoing planning of remaining projects will necessitate strengthened science support for decision making. CERP managers face an array of restoration decisions, including adaptive management based on assessments of restoration performance, near-term operational adjustments, project sequencing, and investments in additional science. The best science should be actively integrated and synthesized to inform these decisions so that restoration benefits are maximized and opportunities for learning across both CERP and non-CERP projects are not lost. New and renewed strategies for monitoring, modeling, and synthesis can strengthen the science support for these decisions.

Some monitoring programs are falling short of their potential, and the value of data sets for decision making is being limited by lack of strategic monitoring design targeted at the information most needed by decision makers. Decisions are best supported when monitoring is strategically designed to address identified management decisions and key management questions, considering natural variability and sampling constraints. Assessing how current monitoring supports decision needs (e.g., adaptive management, operations, and science needs) can focus resources and ensure appropriate data are being collected as the program transitions from a focus on project planning to also support operations and management of the partially restored system.

To better support decision making, the use of models should be expanded, including applications such as assessments of restoration progress and evaluations of future scenarios and vulnerabilities. The CERP has invested significantly to develop a robust set of modeling tools to guide the restoration process, but to date these models have been used mainly for project planning. Restoration decision making would benefit if the CERP could apply its modeling tools to also investigate questions related to restoration progress, adaptive management, and potential future vulnerabilities. Consideration should be given to how these modeling tools can further benefit CERP decision making, including using models to increase understanding of the Everglades ecosystem and its response to changing external conditions. The increased use of models will require additional human and technical capacity for model application and development.

A concerted effort to systematically compare and integrate models and observations is needed to improve decision making. Observations should be compared with model results to better understand model errors and their cause, and to improve model performance. The uncertainty in model predictions should be quantified and used to assess the implications of model uncertainty on decisions. Assimilation of observations and models can also be used to create a more comprehensive view of the current state of the system and can enhance the understanding of the effects of CERP amid natural variability.

A list of priority synthesis topics should be developed annually to advance synthesis in a coordinated way and increase system understanding for management needs. The list should consider the types of synthesis needed to support decision making, the data and information expected to be available, strategies for catalyzing the synthesis, and estimates of resource needs. The skills and expertise of existing synthesis centers, as well as Everglades science experts, should be leveraged to support CERP synthesis needs.

A renewed commitment to best practices in data management from all participants in CERP data collection would better support the value of data to support decision making and promote more comprehensive and nimble synthesis efforts. The use of data to support all types of decision making depends upon effective data management, quality assurance systems, and ease of access to a variety of users. All participants in CERP data collection activities should be required to abide by data quality assurance programs and contribute metadata and data to a central and publicly accessible data management repository in a reasonable time frame.

A nimble organizational infrastructure for science is needed to support restoration decision making in light of the CERP's transition toward operations and adaptive management of multiple completed projects. Information alone does not guarantee effective decision making. Utilizing and integrating scientific information into decision making at appropriate times and in relevant ways is crucial. This infrastructure should include three key elements:

- **Adequate staffing of appropriately trained scientists** that can respond to management needs by analyzing, synthesizing, and communicating evolving relevant scientific information.
- **Continuity of expertise to support adaptive management throughout the life cycle of restoration projects**, bringing technical expertise developed during planning to bear on data analysis and assessment of restoration progress toward goals.
- **Strong science leadership** to provide an efficient and direct linkage between decision makers who need timely summaries of ongoing work and emerging issues and scientists conducting research, modeling, and monitoring. Strong science leadership is also needed to guide future investments in monitoring, modeling, and synthesis toward critical decisions and to help catalyze these efforts.

1

Introduction

The Florida Everglades, formerly a large and diverse aquatic ecosystem, has been dramatically altered during the past century by an extensive water control infrastructure designed to increase regional economic productivity through improved flood management, urban water supply, and agricultural production (Davis and Ogden, 1994). Shaped by the slow flow of water, its vast terrain of sawgrass plains, ridges, sloughs, and tree islands supported a high diversity of plant and animal habitats. This natural landscape also served as a sanctuary for Native Americans. However, large-scale changes to the landscape have diminished the natural resources, and by the mid- to late-20th century many of the area's defining natural characteristics had been lost. The remnants of the original Everglades (see Figure 1-1 and Box 1-1) now compete for vital water with urban and agricultural interests, and contaminated runoff from these two activities impairs the South Florida ecosystem.

Recognition of past declines in environmental quality, combined with continuing threats to the natural character of the remaining Everglades, led to initiation of large-scale restoration planning in the 1990s and the launch of the Comprehensive Everglades Restoration Plan (CERP) in 2000. This unprecedented project envisioned the expenditure of billions of dollars in a multidecadal effort to achieve ecological restoration by reestablishing the hydrologic characteristics of the Everglades, where feasible, and to create a water system that simultaneously serves the needs of both the natural and the human systems of South Florida. Within the social, economic, and political latticework of the 21st century, restoration of the South Florida ecosystem is now under way and represents one of the most ambitious ecosystem renewal projects ever conceived. This report represents the eighth independent assessment of the CERP's progress by the Committee on Independent Scientific Review of Everglades Restoration Progress (CISRERP) of the National Academies of Sciences, Engineering, and Medicine.

THE NATIONAL ACADEMIES AND EVERGLADES RESTORATION

The National Academies has provided scientific and technical advice related to the Everglades restoration since 1999. The National Academies' Committee on the Restoration of the Greater Everglades Ecosystem (CROGEE), which operated from 1999 until 2004, was formed at the request of the South Florida Ecosystem Restoration Task Force (hereafter, simply the Task Force), an intergovernmental body established to facilitate coordination in the restoration effort, and the committee produced six reports (NRC, 2001, 2002a,b, 2003a,b, 2005). The National Academies' Panel to Review the Critical Ecosystem Studies Initiative produced an additional report in 2003 (NRC, 2003c; see Appendix A). The Water Resources Development Act of 2000 (WRDA 2000) mandated that the U.S. Department of the Army, the Department of the Interior, and the State of Florida, in consultation with the Task Force, establish an independent scientific review panel to evaluate progress toward achieving the natural system restoration goals of the CERP. The National Academies' CISRERP was therefore established in 2004 under contract with the U.S. Army Corps of Engineers. After publication of each of the first seven biennial reviews (NASEM, 2016, 2018; NRC, 2007, 2008, 2010, 2012a, 2014; see Appendix A for the report summaries), some members rotated off the committee and some new members were added.

The committee is charged to submit biennial reports that address the following items:

1. An assessment of progress in restoring the natural system, which is defined by section 601(a) of WRDA 2000 as all the land and water managed by the federal government and state within the South Florida ecosystem (see Figure 1-3 and Box 1-1);

2. A discussion of significant accomplishments of the restoration;
3. A discussion and evaluation of specific scientific and engineering issues that may impact progress in achieving the natural system restoration goals of the plan; and
4. An independent review of monitoring and assessment protocols to be used for evaluation of CERP progress (e.g., CERP performance measures, annual assessment reports, assessment strategies).

Given the broad charge, the complexity of the restoration, and the continually evolving circumstances, the committee did not presume it could cover all issues that affect restoration progress in any single report. This report builds on the past reports by this committee (NASEM, 2016, 2018; NRC, 2007, 2008, 2010, 2012a, 2014) and emphasizes restoration progress since 2018, high-priority scientific and engineering issues that the committee judged to be relevant to this time frame, and other issues that have impacted the pace of progress. The committee focused particularly on issues for which the “timing was right”—where the committee’s advice could be useful relative to the decision-making time frames—and on topics that had not been fully addressed in past National Academies Everglades reports. Interested readers should look to past reports by this committee to find detailed discussions of important topics, such as Lake Okeechobee (NASEM, 2018; NRC, 2008), new information impacting the CERP (NASEM, 2016), the need for a midcourse assessment (NASEM, 2016, 2018), climate change (NASEM, 2016; NRC, 2014), invasive species (NRC, 2014), and water quality and quantity challenges and trajectories (NRC, 2010, 2012a). Past reports have also discussed various aspects of the CERP monitoring and assessment plan (NRC, 2004, 2008, 2010, 2012a, 2014), including project-level monitoring (NASEM, 2018).

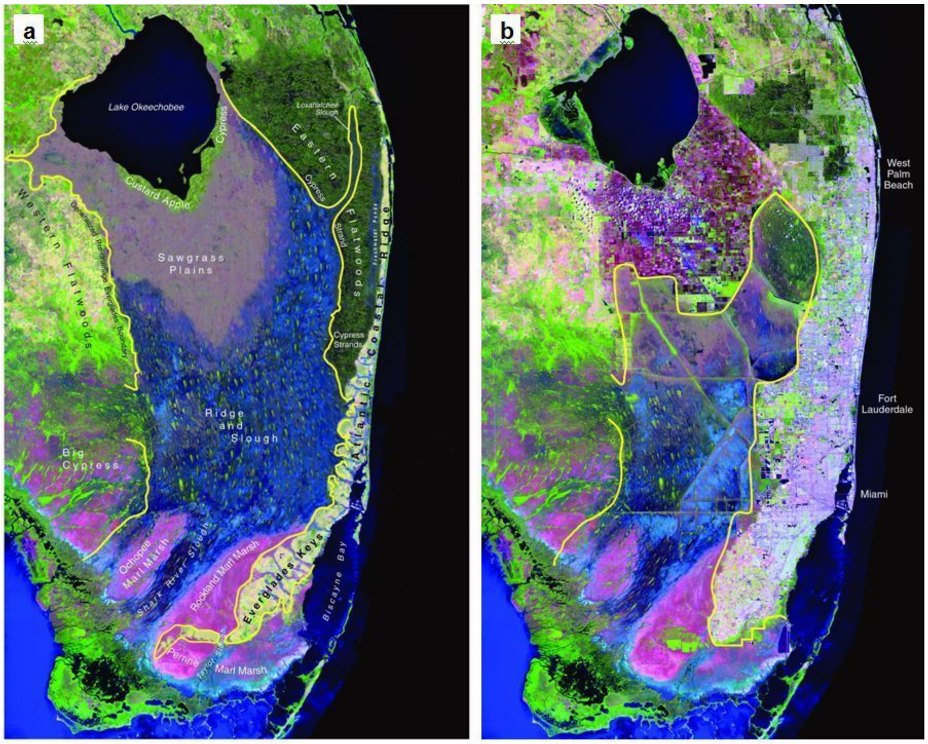


FIGURE 1-1 Reconstructed (a) predrainage (circa 1850) and (b) current (1994) satellite images of the Everglades ecosystem. NOTE: The yellow line in (a) outlines the historical Everglades ecosystem, and the yellow line in (b) outlines the remnant Everglades ecosystem as of 1994. SOURCE: Courtesy of C. McVoy, J. Obeysekera, and W. Said, South Florida Water Management District.

BOX 1-1 Geographic Terms

This box defines some key geographic terms used throughout this report.

- The **Everglades,** the **Everglades ecosystem,** or the **remnant Everglades ecosystem** refers to the present areas of sawgrass, marl prairie, and other wetlands and estuaries south of Lake Okeechobee (Figure 1-1b).
- The **original, historical,** or **predrainage Everglades** refers to the areas of sawgrass, marl prairie, and other wetlands and estuaries south of Lake Okeechobee that existed prior to the construction of drainage canals beginning in the late 1800s (Figure 1-1a).
- The **Everglades watershed** is the drainage that encompasses the Everglades ecosystem but also includes the Kissimmee River watershed and other smaller watersheds north of Lake Okeechobee that ultimately supply water to the Everglades ecosystem.
- The **South Florida ecosystem** (also known as the Greater Everglades Ecosystem; see Figure 1-2) extends from the headwaters of the Kissimmee River near Orlando through Lake Okeechobee and the Everglades into Florida Bay and ultimately the Florida Keys. The boundaries of the South Florida ecosystem are determined by the boundaries of the South Florida Water Management District, the southernmost of the state's five water management districts, although they approximately delineate the boundaries of the South Florida watershed. This designation is important and helpful to the restoration effort because, as many publications have made clear, taking a watershed approach to ecosystem restoration is likely to improve the results, especially when the ecosystem under consideration is as water dependent as the Everglades (NRC, 1999, 2004).
- The **Water Conservation Areas** (WCAs) include WCA-1 (the Arthur R. Marshall Loxahatchee National Wildlife Refuge), -2A, -2B, -3A, and -3B (see Figure 1-2).
- The following represent legally defined geographic terms used in this report:
- The **Everglades Protection Area** is defined in the Everglades Forever Act as comprising WCA-1, -2A, -2B, -3A, and -3B and Everglades National Park.
- The **natural system** is legally defined in the Water Resources Development Act of 2000 (WRDA 2000) as "all land and water managed by the Federal Government or the State within the South Florida ecosystem" (see Figure 1-3). "The term 'natural system' includes (i) water conservation areas; (ii) sovereign submerged land; (iii) Everglades National Park; (iv) Biscayne National Park; (v) Big Cypress National Preserve; (vi) other Federal or State (including a political subdivision of a State) land that is designated and managed for conservation purposes; and (vii) any tribal land that is designated and managed for conservation purposes, as approved by the tribe."

Many maps in this report include shorthand designations that use letters and numbers for engineered additions to the South Florida ecosystem. For example, canals are labeled C-#; levees and associated borrow canals as L-#; and structures, such as culverts, locks, pumps, spillways, control gates, and weirs, as S-# or G-#.

The full committee met in person four times and twice virtually during the course of this review and received briefings at its public meetings from agencies, organizations, and individuals involved in the restoration, as well as from the public. The committee also held six information-gathering web conferences and participated in four field trips. In addition to information received during the meetings, the committee based its assessment of progress on information in relevant CERP and non-CERP restoration documents. The committee's conclusions and recommendations were also informed by a review of relevant scientific literature and the experience and knowledge of the committee members in their fields of expertise. The committee was unable to consider in any detail new materials received after April 2020. The report was originally scheduled for release in September 2020, but a delay in the contract renewal near the end of the study led to a 4-month gap in the review process. Only minor updates were made to the report to reflect major changes during this period.

FIGURE 1-2 The South Florida ecosystem. SOURCE: International Mapping Associates. Reprinted with permission; copyright 2021, International Mapping Associates.

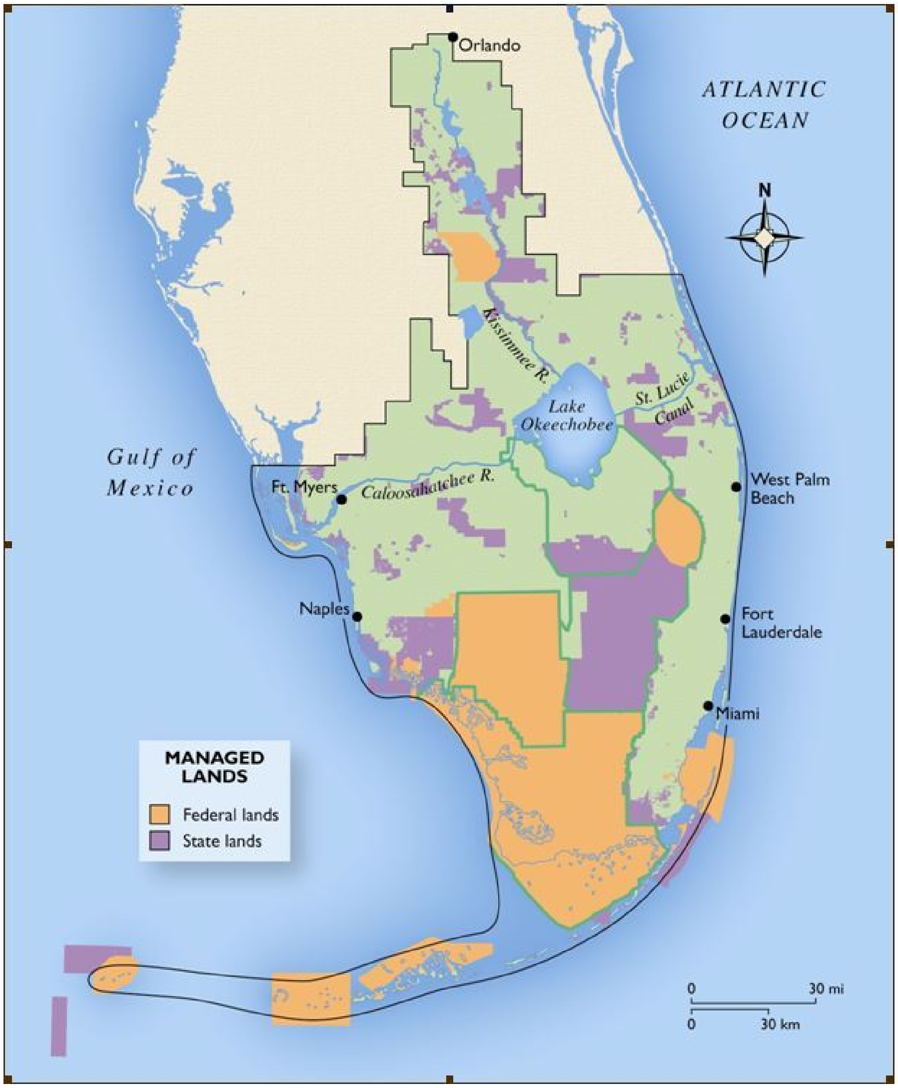


FIGURE 1-3 Land and waters managed by the State of Florida and the federal government as of December 2005 for conservation purposes within the South Florida ecosystem. SOURCE: Based on data compiled by Florida State University's Florida Natural Areas Inventory (http://www.fnai.org/gisdata.cfm), International Mapping Associates. Reprinted with permission; copyright 2021, International Mapping Associates.

REPORT ORGANIZATION

In Chapter 2, the committee provides an overview of the CERP in the context of other ongoing restoration activities and discusses the restoration goals that guide the overall effort. In Chapter 3, the committee analyzes the natural system restoration progress associated with CERP and non-CERP projects, along with programmatic factors and planning efforts that affect future progress. In Chapter 4, the committee reviews the benefits provided by the Combined Operating Plan (COP), its planning process, and the opportunities presented through adaptive management. In Chapter 5, the committee performs an in-depth analysis of estuaries and coastal systems within the context of CERP projects. In Chapter 6, the committee discusses systems thinking and science to support decision making.

2

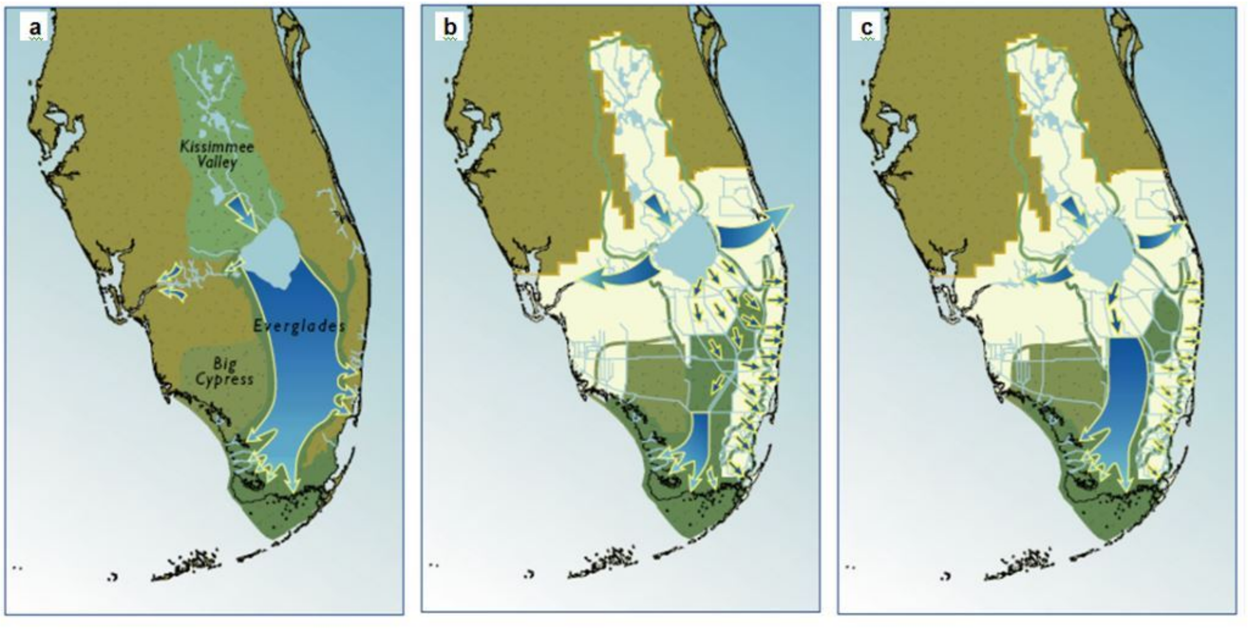
The Restoration Plan in Context

This chapter sets the stage for the eighth of this committee's biennial assessments of restoration progress in the South Florida ecosystem. Background for understanding the project is provided through descriptions of the ecosystem decline, restoration goals, the needs of a restored ecosystem, and the specific activities of the restoration project.

BACKGROUND

The Everglades once encompassed about 3 million acres of slow-moving water and associated biota that stretched from Lake Okeechobee in the north to the Florida Keys in the south (Figures 1-1a and 2-1a). The conversion of the Everglades wilderness into an area of high agricultural productivity and cities was a dream of 19th-century investors, and projects begun between 1881 and 1894 affected the flow of water in the watershed north of Lake Okeechobee. These early projects included dredging canals in the Kissimmee River Basin and constructing a channel connecting Lake Okeechobee to the Caloosahatchee River and, ultimately, the Gulf of Mexico. By the late 1800s, more than 50,000 acres north and west of the lake had been drained and cleared for agriculture (Grunwald, 2006). In 1907, Governor Napoleon Bonaparte Broward created the Everglades Drainage District to construct a vast array of ditches, canals, dikes, and "improved" channels. By the 1930s, Lake Okeechobee had a second outlet, through the St. Lucie Canal, leading to the Atlantic Ocean, and 440 miles of other canals altered the hydrology of the Everglades (Blake, 1980). After hurricanes in 1926 and 1928 resulted in disastrous flooding from Lake Okeechobee, the U.S. Army Corps of Engineers (USACE) replaced the small berm that bordered the southern edge of the lake with the massive Herbert Hoover Dike, which was eventually expanded in the 1960s to encircle the lake. The hydrologic end product of these drainage activities was the drastic reduction of natural water storage within the system and an increased susceptibility to drought and desiccation in the southern reaches of the Everglades (NRC, 2005).

After further flooding in 1947 and increasing demands for improved agricultural production and flood management for the expanding population centers on the southeast Florida coast, the U.S. Congress authorized the Central and Southern Florida Project. This project provided flood management and urban and agricultural water supply by straightening 103 miles of the meandering Kissimmee River, expanding the Herbert Hoover Dike, constructing a levee along the eastern boundary of the Everglades to prevent flows into the southeastern urban areas, establishing the 700,000-acre Everglades Agricultural Area (EAA) south of Lake Okeechobee, and creating a series of Water Conservation Areas (WCAs) in the remaining space between the lake and Everglades National Park (Light and Dineen, 1994). The eastern levee isolated about 100,000 acres of the Everglades ecosystem, making it available for development (Lord, 1993). In total, urban and agricultural development have reduced the Everglades to about one-half its predrainage area (see Figure 1-1b; Davis and Ogden, 1994) and have contaminated its waters with chemicals such as phosphorus, nitrogen, sulfur, mercury, and pesticides. Associated drainage and flood management structures, including the Central and Southern Florida Project, have diverted large quantities of water directly east and west to the northern estuaries, thereby reducing the dominantly southward freshwater flows and natural water storage that defined the ecosystem (see Figure 2-1b).



Pre-drainage Flow **Current Flow** **Restored Flow**

FIGURE 2-1 Water flow in the Everglades under (a) historical conditions, (b) current conditions, and (c) conditions envisioned upon completion of the Comprehensive Everglades Restoration Plan. White areas outline the northern extent of the South Florida ecosystem (see Box 1-1 and Figure 1-2). SOURCE: Graphics provided by USACE, Jacksonville District.

The profound hydrologic alterations were accompanied by many changes in the biotic communities in the ecosystem, including reductions and changes in the composition, distribution, and abundance of the populations of wading birds. Today, the federal government has listed 78 plant and animal species in South Florida as threatened or endangered, with many more included on state lists. Some distinctive Everglades habitats, such as custard apple forests and peripheral wet prairie, have disappeared altogether, while other habitats are severely reduced in area (Davis and Ogden, 1994; Marshall et al., 2004). Approximately 1 million acres are contaminated with mercury from atmospheric deposition (McPherson and Halley, 1996; Orem et al., 2011). Phosphorus from agricultural runoff has impacted water quality in large portions of the Everglades and has been particularly problematic in Lake Okeechobee (Flaig and Reddy, 1995). The Caloosahatchee and St. Lucie estuaries, including parts of the Indian River Lagoon, have been greatly altered by high and extremely variable freshwater discharges that bring nutrients and contaminants and disrupt salinity regimes (Doering, 1996; Doering and Chamberlain, 1999).

At least as early as the 1920s, private citizens were calling attention to the degradation of the Florida Everglades (Blake, 1980). However, by the time Marjory Stoneman Douglas's classic book *The Everglades: River of Grass* was published in 1947 (the same year that Everglades National Park was dedicated), the South Florida ecosystem had already been altered extensively. Beginning in the 1970s, prompted by concerns about deteriorating conditions in Everglades National Park and other parts of the South Florida ecosystem, the public, as well as the federal and state governments, directed increased attention to the adverse ecological effects of the flood management and irrigation projects (Kiker et al., 2001; Perry, 2004). By the late 1980s it was clear that various minor corrective measures undertaken to remedy the situation were insufficient. As a result, a powerful political consensus developed among federal agencies, Native American tribes, state agencies and commissions, county governments, and conservation organizations that a large restoration effort was needed in the Everglades (Kiker et al., 2001). This recognition culminated in the Comprehensive Everglades Restoration Plan (CERP), authorized by Congress in 2000, which builds on other ongoing restoration activities of the state and federal governments to create what was at the time the most ambitious restoration effort in the nation's history.

RESTORATION GOALS FOR THE EVERGLADES

Several goals have been articulated for the restoration of the South Florida ecosystem, reflecting the various restoration programs. The South Florida Ecosystem Restoration Task Force (hereafter, simply the Task Force), an intergovernmental body established to facilitate coordination in the restoration effort, has three broad strategic goals: (1) "get the water right," (2) "restore, preserve, and protect natural habitats and species," and (3) "foster compatibility of the built and natural systems" (SFERTF, 2000). These goals encompass, but are not limited to, the CERP. The Task Force works to coordinate and build consensus among the many non-CERP restoration initiatives that support these broad goals.

The goal of the CERP, as stated in the Water Resources Development Act of 2000, is "restoration, preservation, and protection of the South Florida Ecosystem while providing for other water-related needs of the region, including water supply and flood protection." The Programmatic Regulations (33 CFR § 385.3) that guide implementation of the CERP further clarify this goal by defining restoration as "the recovery and protection of the South Florida ecosystem so that it once again achieves and sustains those essential hydrological and biological characteristics that defined the undisturbed South Florida ecosystem." These defining characteristics include a large areal extent of interconnected wetlands, extremely low concentrations of nutrients in freshwater wetlands, sheet flow, healthy and productive estuaries, resilient plant communities, and an abundance of native wetland animals (DOI and USACE, 2005). Although development has permanently reduced the areal extent of the Everglades ecosystem, the CERP hopes to recover many of the Everglades' original characteristics and natural ecosystem processes in the remnant Everglades. At the same time, the CERP is charged to maintain levels of flood protection (as of 2000) and was designed to provide for other water-related needs, including water supply (DOI and USACE, 2005).

Although the CERP contributes to each of the Task Force's three goals, it focuses primarily on restoring the hydrologic features of the undeveloped wetlands remaining in the South Florida ecosystem, on the assumption that improvements in ecological conditions will follow. Originally, "getting the water right" had four components—quality, quantity, timing, and distribution. However, the hydrologic properties of flow, encompassing the concepts of direction, velocity, and discharge, have been recognized as an important component of getting the water right that had previously been overlooked (NRC, 2003c; SCT, 2003). Numerous studies have supported the general approach to getting the water right (Davis and Ogden, 1994; NRC, 2005; SSG, 1993), although it is widely recognized that recovery of the native habitats and species in South Florida may require restoration efforts in addition to getting the water right, such as controlling non-native species and reversing the decline in the spatial extent and compartmentalization of the natural landscape (SFERTF, 2000; SSG, 1993).

The goal of ecosystem restoration can seldom be the exact re-creation of some historical or preexisting state because physical conditions, driving forces, and boundary conditions usually have changed and are not fully recoverable. Rather, restoration is better viewed as the process of assisting the recovery of a degraded ecosystem to the point where it contains sufficient biotic and abiotic resources to continue its functions without further assistance in the form of energy or other resources from humans (NRC, 1996; Society for Ecological Restoration International Science & Policy Working Group, 2004). The term *ecosystem rehabilitation* may be more appropriate when the objective is to improve conditions in a part of the South Florida ecosystem to at least some minimally acceptable level that allows the restoration of the larger ecosystem to advance. However, flood management remains a critical aspect of the CERP design because improving hydrology and sheet flow in extensive wetland areas has the potential, through seepage, to flood adjacent urban and agricultural areas. Artificial storage will be required to replace the lost natural storage in the system (NRC, 2005), and groundwater management also requires attention to boundaries between developed and natural areas. For these and other reasons, even when the CERP is complete, it will require large inputs of energy and human effort to operate and maintain pumps, stormwater treatment areas, canals and levees, and reservoirs, and to continue to manage non-native species. Thus, for the foreseeable future, the CERP does not envision ecosystem restoration or rehabilitation that returns the ecosystem to a state where it can "manage itself."

The broad CERP goals should be interpreted in the context of the complex Everglades ecosystem in order to guide restoration efforts. Early restoration was motivated by ambitious albeit generalized expectations for the ecosystem. For example, the CERP conceptual plan, also called the Yellow Book (USACE and SFWMD, 1999), stated: "At all levels in the aquatic food chains, the numbers of such animals as crayfish, minnows, sunfish, frogs, alligators, herons, ibis, and otters, will markedly increase." Currently the goals for the restoration upon which policy makers agree (USACE et al., 2007) are largely qualitative, indicating a desired direction of change for a number of indicators, without a quantitative objective, providing no clear expectation of how the success of restoration efforts should collectively be assessed. Systemwide ecological indicators with quantitative targets have been established by restoration scientists for assessing restoration success (Brandt et al., 2018; Doren et al., 2009), but these targets have not been endorsed for use in restoration planning. Continued investment in Everglades restoration proceeds based on improving the current undesirable state of the system rather than toward a specific set of quantitative characteristics desired for the future South Florida ecosystem.

An additional factor challenging the ability of the restoration efforts to meet the "essential hydrological and biological characteristics that defined the undisturbed South Florida ecosystem" is ongoing climate change, including changes in precipitation patterns, sea-level rise, and ocean warming. Not only did irreversible changes occur since the 19th century, but also, since the development of the CERP, mean sea levels at Key Largo have risen approximately 11 cm[1] and future projections call for further increases of as much as 2 m in South Florida in the 21st century (NOAA, 2017).

Implicit in the understanding of ecosystem restoration is the recognition that natural systems are self-designing and dynamic, and therefore it is not possible to know in advance exactly what can or will be achieved. Thus, ecosystem restoration proceeds in the face of scientific uncertainty and must consider a range of possible future conditions. NASEM (2016) discusses the challenges to restoration goals arising from major changes that have occurred since the inception of the CERP in 1999, and NASEM (2018) recommended that agencies anticipate and design for the Everglades of the future, rather than focusing restoration only on the past Everglades.

What Restoration Requires

Restoring the South Florida ecosystem to a desired ecological landscape requires reestablishment of critical processes that sustain its functioning. Although getting the water right is the oft-stated and immediate goal, the restoration ultimately aims to restore the distinctive characteristics of the historical ecosystem to the remnant Everglades (DOI and USACE, 2005). Getting the water right is a means to that end, not the end itself. The hydrologic and ecological characteristics of the historical Everglades serve as general restoration goals for a functional (albeit reduced in size) Everglades ecosystem. The first Committee on Independent Scientific Review of Everglades Restoration Progress (CISRERP) identified five critical components of Everglades restoration (NRC, 2007):

1. Enough water storage capacity combined with operations that allow for appropriate volumes of water to support healthy estuaries and the return of sheet flow through the Everglades ecosystem while meeting other demands for water;
2. Mechanisms for delivering and distributing the water to the natural system in a way that resembles historical flow patterns, affecting volume, depth, velocity, direction, distribution, and timing of flows;

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[1] See https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8724580.

3. Barriers to eastward seepage of water so that higher water levels can be maintained in parts of the Everglades ecosystem without compromising the current levels of flood protection of developed areas as required by the CERP;
4. Methods for securing water quality conditions compatible with restoration goals for a natural system that was inherently extremely nutrient poor, particularly with respect to phosphorus; and
5. Retention, improvement, and expansion of the full range of habitats by preventing further losses of critical wetland and estuarine habitats, and by protecting lands that could usefully be part of the restored ecosystem.

If these five critical components of restoration are achieved and the difficult problem of invasive species can be managed, then the basic physical, chemical, and biological processes that created the historical Everglades can once again work to create and sustain a functional mosaic of biotic communities that resemble what was distinctive about the historical Everglades albeit of a reduced scale.

The history of the Everglades and ongoing global climate change and sea-level rise will make replication of the predrainage system impossible. Because of the historical changes that have occurred through engineered structures, urban development, introduced species, and other factors, the paths taken by the ecosystem and its components in response to restoration efforts will not retrace the paths taken to reach current conditions. End results will also often differ from the historical system as climate change and sea-level rise, permanently established invasive species, and other factors have moved the ecosystem away from its historical state (Hiers et al., 2012) and will continue to change the restored system in the future. The specific nature and extent of the functional mosaic thus depends on not only the degree to which the five critical components can be achieved but also future precipitation patterns, rising sea levels, marine incursion into estuaries and coastal wetlands, as well as continued investment in water and ecological management.

Even if the restored system does not exactly replicate the historical system, or reach all the biological, chemical, and physical targets, the reestablishment of natural processes and dynamics should result in a viable and valuable Everglades ecosystem under current conditions. The central principle of ecosystem management is to provide for the natural processes that historically shaped an ecosystem, because ecosystems are characterized by the processes that regulate them. How the reestablished processes interact with future changes within and external to the system will determine the future character of the ecosystem, its species, and communities.

RESTORATION ACTIVITIES

Several restoration programs, including the largest of the initiatives, the CERP, are now under way. The CERP often builds upon non-CERP activities (also called "foundation projects"), many of which are essential to the effectiveness of the CERP. The following section provides a brief overview of the CERP and some of the major non-CERP activities.

Comprehensive Everglades Restoration Plan

The Water Resources Development Act of 2000 authorized the CERP as the framework for modifying the Central and South Florida Project. Considered a blueprint for the restoration of the South Florida ecosystem, the CERP is led by two organizations with considerable expertise managing the water resources of South Florida— the USACE, which built most of the canals and levees throughout the region, and the South Florida Water Management District (SFWMD), the state agency with primary responsibility for operating and maintaining this complicated water collection and distribution system.

The CERP conceptual plan (USACE and SFWMD, 1999) proposes major alterations to the Central and South Florida Project in an effort to reverse decades of ecosystem decline. The Yellow Book includes 68 project components to be constructed at an estimated cost of approximately $23.2 billion (in

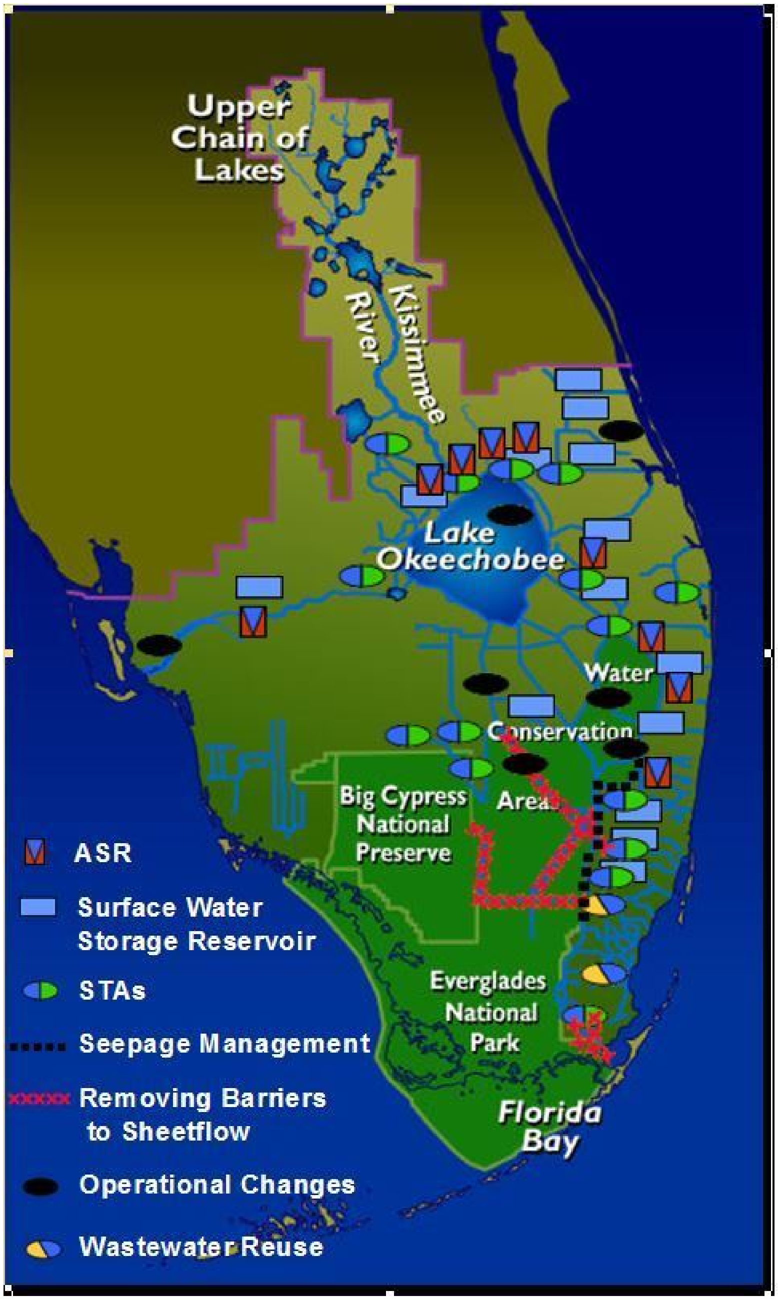

FIGURE 2-2 Major project components of the CERP as outlined in 1999. SOURCE: Courtesy of Laura Mahoney, USACE.

2019 dollars, including program coordination and monitoring costs; USACE and DOI, 2020; Figure 2-2). Major components of the restoration plan focus on restoring the quantity, quality, timing, and distribution of water for the South Florida ecosystem. The Yellow Book outlines the major CERP components, including the following:

- **Conventional surface-water storage reservoirs.** The Yellow Book includes plans for approximately 1.5 million acre-feet of storage, located north of Lake Okeechobee, in the St. Lucie and Caloosahatchee Basins, in the EAA, and in Palm Beach, Broward, and Miami-Dade counties.

- **Aquifer storage and recovery (ASR).** The Yellow Book proposes to provide substantial water storage through ASR, a highly engineered approach that would use a large number of wells built around Lake Okeechobee, in Palm Beach County, and in the Caloosahatchee Basin to store water approximately 1,000 feet below ground.
- **In-ground reservoirs.** The Yellow Book proposes additional water storage in quarries created by rock mining.
- **Stormwater treatment areas (STAs).** The CERP contains plans for additional constructed wetlands that will treat agricultural and urban runoff water before it enters natural wetlands.[2]
- **Seepage management.** The Yellow Book outlines seepage management projects to prevent unwanted loss of water from the remnant Everglades through levees and groundwater flow. The approaches include adding impermeable barriers to the levees, installing pumps near levees to redirect lost water back into the Everglades, and holding water levels higher in undeveloped areas between the Everglades and the developed lands to the east.
- **Removing barriers to sheet flow.** The CERP includes plans for removing 240 miles of levees and canals, to reestablish shallow sheet flow of water through the Everglades ecosystem.
- **Rainfall-driven water management.** The Yellow Book includes operational changes in the water delivery schedules to the WCAs and Everglades National Park to mimic more natural patterns of water delivery and flow through the system.
- **Water reuse and conservation.** To address shortfalls in water supply, the Yellow Book proposes two advanced wastewater treatment plants so that the reclaimed water could be discharged to wetlands along Biscayne Bay or used to recharge the Biscayne aquifer.

The largest portion of the budget is devoted to storage projects and to acquiring the lands needed for them.

The modifications to the Central and Southern Florida Project embodied in the CERP were originally expected to take more than three decades to complete (and will likely now take much longer), and to be effective they require a clear strategy for managing and coordinating restoration efforts. The Everglades Programmatic Regulations (33 CFR Part 385) state that decisions on CERP implementation are made by the USACE and the SFWMD (or any other local project sponsors), in consultation with the Department of the Interior, the Environmental Protection Agency (EPA), the Department of Commerce, the Miccosukee Tribe of Indians of Florida, the Seminole Tribe of Florida, the Florida Department of Environmental Protection, and other federal, state, and local agencies (33 CFR Part 385).

The Water Resources Development Act of 2000 endorses the use of an adaptive management framework for the restoration process, and the Programmatic Regulations (33 CFR §385.31[a]) formally establish an adaptive management program that will

> assess responses of the South Florida ecosystem to implementation of the Plan; . . . [and] seek continuous improvement of the Plan based upon new information resulting from changed or unforeseen circumstances, new scientific and technical information, new or updated modeling;

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[2] Although some STAs are included among CERP projects, the USACE has clarified its policy on federal cost sharing for water quality features. A memo from the Assistant Secretary of the Army (Civil Works) (USACE, 2007) states: “Before there can be a Federal interest to cost share a WQ [water quality] improvement feature, the State must be in compliance with WQ standards for the current use of the water to be affected and the work proposed must be deemed essential to the Everglades restoration effort.” The memo goes on to state, “the Yellow Book specifically envisioned that the State would be responsible for meeting water quality standards.” However, the Secretary of the Army can recommend to Congress that project features deemed “essential to Everglades restoration” be cost shared. In such cases, the state is responsible for 100 percent of the costs to treat water to state standards for its current use, and federal cost sharing is determined based on the additional treatment needed to meet the requirements of Everglades restoration (K. Taplin, USACE, personal communication, 2018).

> information developed through the assessment principles contained in the Plan; and future authorized changes to the Plan. . . .

An interagency body called Restoration, Coordination, and Verification (RECOVER; see Box 2-1) was established early in the development of the CERP to ensure that sound science is used in the restoration. The RECOVER leadership group oversees the monitoring and assessment program that will evaluate the progress of the CERP toward restoring the natural system and will assess the need for changes to the plan through the adaptive management process (see also Chapter 6).

Non-CERP Restoration Activities

When Congress authorized the CERP in the Water Resources and Development Act of 2000, the SFWMD, the USACE, the National Park Service, and the U.S. Fish and Wildlife Service were already implementing several activities intended to restore key aspects of the Everglades ecosystem. These non-CERP initiatives are critical to the overall restoration progress. In fact, the CERP's effectiveness was predicated upon the completion of many of these projects, which include Modified Water Deliveries to Everglades National Park, C-111 South Dade, and state water quality treatment projects developed under the Everglades Construction Project (see Figure 2-3). State efforts to improve the quality of water flowing into the remnant Everglades continue under the Restoration Strategies program. Recent progress on key non-CERP projects with critical linkages to the CERP are described in Chapter 3.

Major Developments and Changing Context Since 2000

Several major program-level developments have occurred since the CERP was launched that have affected the pace and focus of CERP efforts. In 2004, Florida launched Acceler8, a plan to hasten the pace of project implementation that was bogged down by the slow federal planning process (for further discussion of Acceler8, see NRC, 2007). Acceler8 originally included 11 CERP project components and 1

BOX 2-1 RECOVER

RECOVER (Restoration Coordination and VERification) is multiagency team, whose role is to "organize and apply scientific and technical information in ways that are most effective in supporting the CERP's objectives." "RECOVER does this by applying a system-wide perspective to the planning and implementation of the CERP" (RECOVER, 2021).

The work of RECOVER is envisioned to fall within three main areas:

1. **Evaluation**—to evaluate, using numerical modeling and other tools, the performance of project and program plans and designs to ensure that they are fully linked to the systemwide goals and purposes of the CERP.
2. **Assessment**—to develop and implement an appropriate ecological monitoring program in order to establish prerestoration environmental conditions and track and define ecological response as restoration progresses, and to provide the systemwide science perspective necessary to prudently ensure projects meet intended objectives and to guide planning and operations in order to maximize benefits to the natural system.
3. **Planning**—to identify and provide analyses regarding potential improvements in the design and operation of the CERP, consistent with the CERP objectives, and to strive for consensus regarding scientific and technical aspects of the CERP.

SOURCE: RECOVER, 2021.

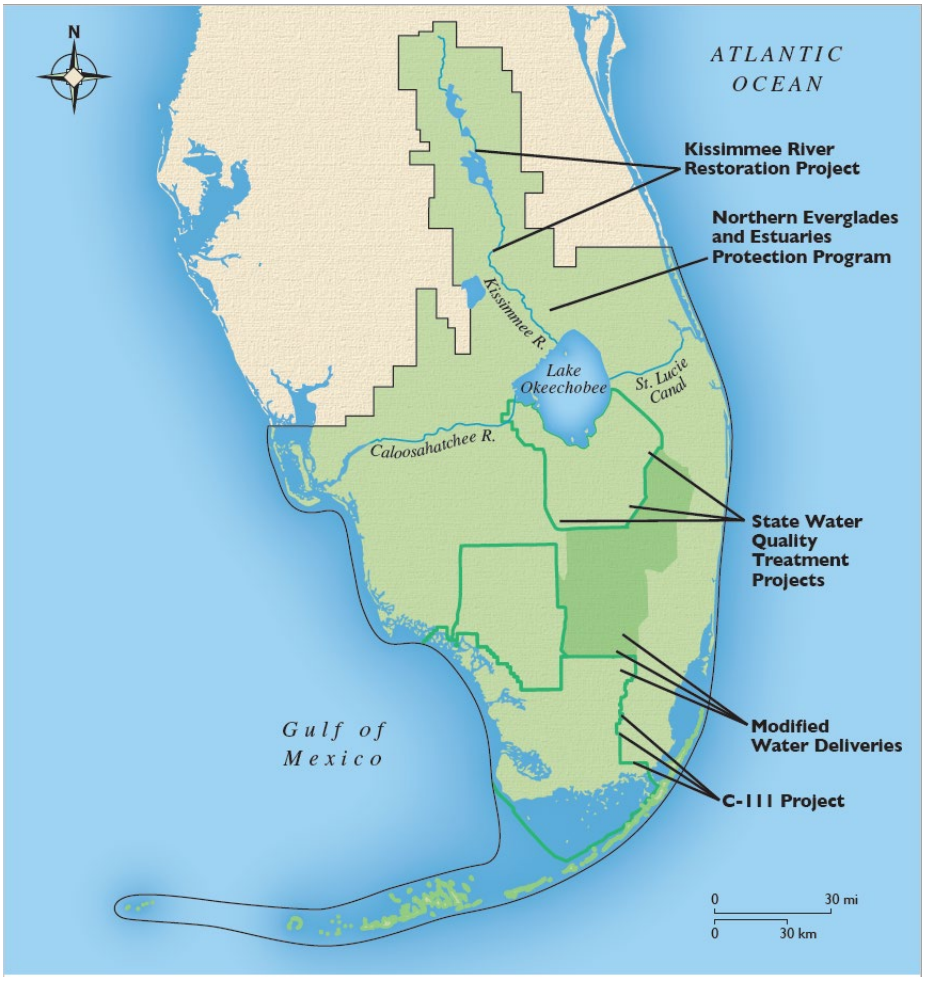

FIGURE 2-3 Locations of major non-CERP initiatives. SOURCE: International Mapping Associates. Reprinted with permission; copyright 2021, International Mapping Associates.

non-CERP project, and although the state was unable to complete all the original tasks, the program led to increased state investment and expedited project construction timelines for several CERP projects.

Operation of Lake Okeechobee has been modified twice since the CERP was developed in ways that have reduced total storage. In April 2000, the Water Supply and Environment regulation schedule was implemented to reduce high-water impacts on the lake's littoral zone and to reduce harmful high discharges to the St. Lucie and Caloosahatchee estuaries. The regulation schedule was changed again in 2008 to reduce the risk of failure of the Herbert Hoover Dike until the USACE could make critical repairs. This resulted in a loss of 564,000 acre-feet (AF) of potential storage from the regional system (see NASEM, 2016).

In the years since the CERP was launched, the State of Florida has increasingly encouraged the use of alternative water supplies—including wastewater, stormwater, and excess surface water—to meet future water demands (e.g., FDEP, 2015). In 2006, the SFWMD passed the Lower East Coast Regional Water Availability Rule, which caps groundwater withdrawals at 2006 levels, requiring urban areas to meet increased demand through a combination of conservation and alternative water supplies. In 2007, the Florida legislature mandated that ocean wastewater discharges in South Florida be eliminated and 60 percent of those discharges be reused by 2025 (Fla. Stat. § 403.086[9]), representing approximately 180 million gallons per day of new water supply for the Lower East Coast. It remains unclear whether or how these new initiatives and mandates will affect the expectations for agricultural and urban water supply from the CERP, particularly because the capture of excess surface water is a key element of the CERP.

In 2010, EPA issued its court-ordered Amended Determination, which directed the state of Florida to correct deficiencies in meeting the narrative and numeric nutrient criteria in the Everglades Protection Area (EPA, 2010). In 2012, the State of Florida launched its Restoration Strategies Regional Water Quality Plan, which was approved by EPA and the Court as an alternative means to address the Amended Determination. The State of Florida is currently in the process of constructing approximately 6,500 acres of new STAs and three flow equalization basins (116,000 AF; see Chapter 3). These water quality treatment improvements are designed so that water leaving the STAs will meet a new water quality–based effluent limit (WQBEL) to comply with the 10 parts per billion (ppb) total phosphorus water quality criterion for the Everglades Protection Area.[3]

Changing Understanding of Restoration Challenges

Much new knowledge has been gained since the launch of the CERP that provides a new understanding of restoration challenges and opportunities and informs future restoration planning and management. Considering the many advances in knowledge since 1999, climate change and sea-level rise are among the most significant. As outlined in NASEM (2016), changes in precipitation and evapotranspiration are expected to have substantial impacts on CERP outcomes. Downscaled precipitation projections remain uncertain and range from modest increases to sizable decreases for South Florida, and research continues locally and nationally to improve these projections. Sea-level rise is already affecting the distribution of Everglades habitats and causing coastal flooding in some low-lying urban areas. CERP planners are now evaluating all future restoration benefits in the context of low, medium, and high sea-level rise projections, although recent CISRERP reports (NASEM, 2016, 2018; NRC, 2014) have recommended greater consideration of climate change and sea-level rise in CERP project and program planning.

Since the CERP was developed, the significance of invasive species management for the success of restoration has also been recognized by the South Florida Ecosystem Restoration Task Force and its member agencies.[4] Non-native species constitute a substantial proportion of the current biota of the Everglades. The approximately 250 non-native plant species are about 16 percent of the regional flora (see NRC, 2014). South Florida has a subtropical climate with habitats that are similar to those from which many of the invaders originate, with relatively few native species in many taxa to compete with introduced ones. Some species, especially of introduced vascular plants and reptiles, have had dramatic effects on the structure and functioning of Everglades ecosystems, and necessitate aggressive management and early detection of new high-risk invaders to ensure that ongoing CERP efforts to get the water right allow native species to prosper instead of simply enhancing conditions for invasive species.

SUMMARY

The Everglades ecosystem is one of the world’s ecological treasures, but for more than a century the installation of an extensive water management infrastructure has changed the geography of South Florida and has facilitated extensive agricultural and urban development. These changes have had profound ancillary effects on regional hydrology, vegetation, and wildlife populations. The CERP, a joint

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[3] The WQBEL is a numeric discharge limit used to regulate permitted discharges from the STAs so as to not exceed a long-term geometric mean of 10 ppb within the Everglades Protection Area. This numeric value is now translated into a flow-weighted mean (FWM) total phosphorus (TP) concentration and applied to each STA discharge point, which now must meet the following: (1) the STAs are in compliance with WQBEL when the TP concentration of STA discharge point does not exceed an annual FWM of 13 ppb in more than 3 out of 5 years, and (2) annual FWM of 19 ppb in any water year (Fla. Stat. §373.4592; EPA, 2010; Leeds, 2014).

[4] See http://www.evergladesrestoration.gov/content/ies.

effort led by the state and federal governments and launched in 2000, seeks to reverse the general decline of the ecosystem. Since 2000, the legal context for the CERP and other major Everglades restoration efforts has evolved and the scientific understanding of Everglades restoration and its current and future stressors has expanded, and the programs continue to adapt. Implementation progress is discussed in detail in Chapter 3.

3

Restoration Progress

This committee is charged with the task of discussing accomplishments of the restoration and assessing “the progress toward achieving the natural system restoration goals of the Comprehensive Everglades Restoration Plan [CERP]” (see Chapter 1 for the statement of task and Chapter 2 for a discussion of restoration goals). In this chapter, the committee updates the National Academies’ previous assessments of CERP and related non-CERP restoration projects (NASEM, 2016, 2018; NRC, 2007, 2008, 2010, 2012a, 2014). The committee also addresses programmatic and implementation progress and discusses the ecosystem benefits resulting from the progress to date.

PROGRAMMATIC PROGRESS

To assess programmatic progress the committee reviewed a set of primary issues that influence CERP progress toward its overall goals of ecosystem restoration. These issues, described in the following sections, relate to project authorization, funding, and project scheduling.

Project Authorization

Once project planning is complete, CERP projects with costs exceeding $25 million must be individually authorized by Congress before they can receive federal appropriations. Water Resources Development Acts (WRDAs) have served as the mechanism to congressionally authorize U.S. Army Corps of Engineers (USACE) projects. In the 20 years since the CERP was launched in WRDA 2000, five WRDA bills have been enacted:

- WRDA 2007 (Public Law 110-114), which authorized Indian River Lagoon-South, Picayune Strand Restoration, and the Site 1 Impoundment projects;
- Water Resources Reform and Development Act (WRRDA) 2014 (Public Law 113-121), which authorized four additional projects (C-43 Reservoir, C-111 Spreader Canal [Western], Biscayne Bay Coastal Wetlands [Phase 1], and Broward County Water Preserve Areas [WPAs]);
- WRDA 2016 (Title I of the Water Infrastructure Improvements for the Nation Act [WIIN Act]; Public Law 114-322), which includes authorization for the $1.9 billion Central Everglades Planning Project (CEPP). WRDA 2016 also authorized changes to the Picayune Strand Restoration Project related to cost escalations to allow for its completion;
- WRDA 2018 (Public Law 115-270), which authorized the CEPP postauthorization change report, which included the 240,000 acre-foot (AF) Everglades Agricultural Area (EAA) Storage Reservoir; and
- WRDA 2020 (Public Law 116-260), which authorized the Loxahatchee Watershed Restoration Project and combined the EAA Storage Reservoir and CEPP into a single project.

The occurrence of WRDAs every 2 years (since 2014) has ensured that the authorization process does not pose delays on CERP restoration progress.

Authorized CERP projects are sometimes classified by the WRDA bills in which they were authorized—Generation 1 (WRDA 2007), 2 (WRDA 2014), 3 (WRDA 2016 and 2018), and 4 (WRDA

2020), with the Melaleuca Eradication Project, which was authorized under programmatic authority, included in Generation 1.

Funding

Changes in funding can illuminate progress or programmatic constraints on implementation. Funding for Everglades restoration has significantly increased over the past 2 years, achieving rates of funding in fiscal years (FY) 2020 and 2021 (requested) that for the first time exceed the original CERP vision of $200 million of state and $200 million of federal funds annually. The history of federal funding for the CERP is illustrated in Figure 3-1, which includes construction funds and support for planning, design, coordination, and monitoring. After a significant decrease to $44 million in FY 2014, federal funding for the CERP increased to between $70 and $105 million over the 5 years FY 2015-2019. In FY 2020, federal CERP funding totaled $247 million, and $257 million has been requested for FY 2021. These would be only the second and third years (2010 was the first) when federal appropriations met or exceeded funding rates envisioned in the original 1999 CERP plan. Over the most recent 5-year period, FY 2016-2020, for which data are available, federal funding for Everglades restoration (including both CERP and non-CERP efforts) averaged $247 million per year, with $125 million for CERP and $123 million for non-CERP efforts (Figure 3-2).

State budgets for the CERP have sharply increased in recent years, while non-CERP funding has remained steady (Figures 3-1 and 3-2). State CERP funding in FY 2020 reached nearly $373 million and has exceeded $200 million in each of the last 4 fiscal years, consistent with the original CERP vision and more than doubling CERP funding levels compared to the previous 5 fiscal years. State non-CERP funding totaled $602 million in FY 2020 and averaged $593 million over the past 5 fiscal years. Total state restoration funding (CERP and non-CERP) has exceeded $775 million per year since FY 2017, a level last reached in FY 2011. FY 2021 state funding requests for CERP of $264 million and non-CERP of $582 million continue this level of increased state investment in restoration (SFERTF, 2021). These increased levels of both state and federal funding support increased construction progress compared to earlier years, leading to faster restoration of benefits and potentially mitigating ongoing ecosystem degradation.

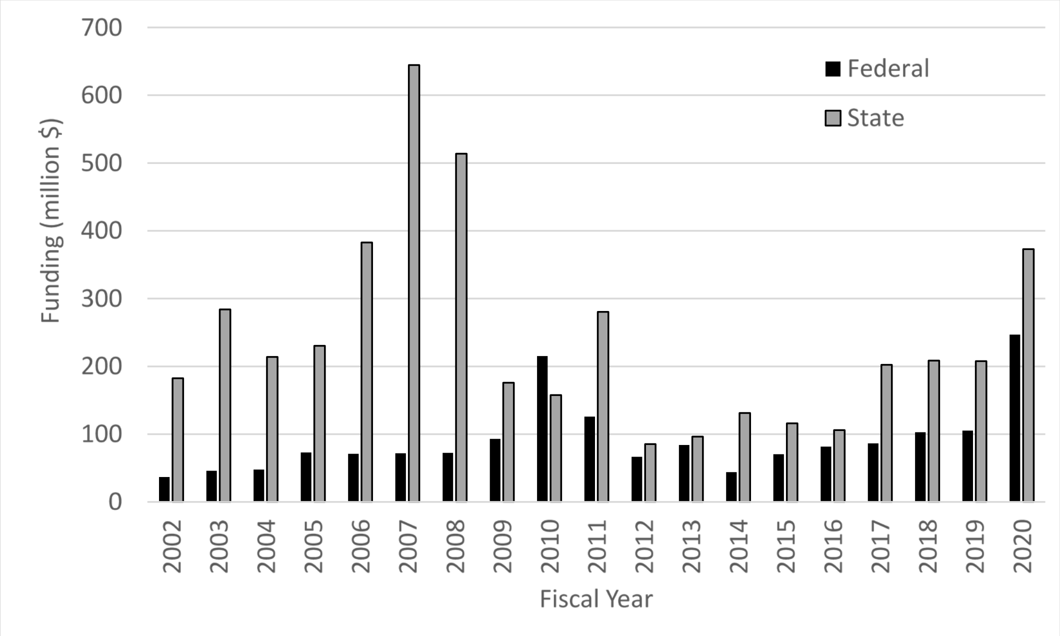

FIGURE 3-1 Federal and state funding for the CERP. SOURCE: Data from SFERTF, 2021.

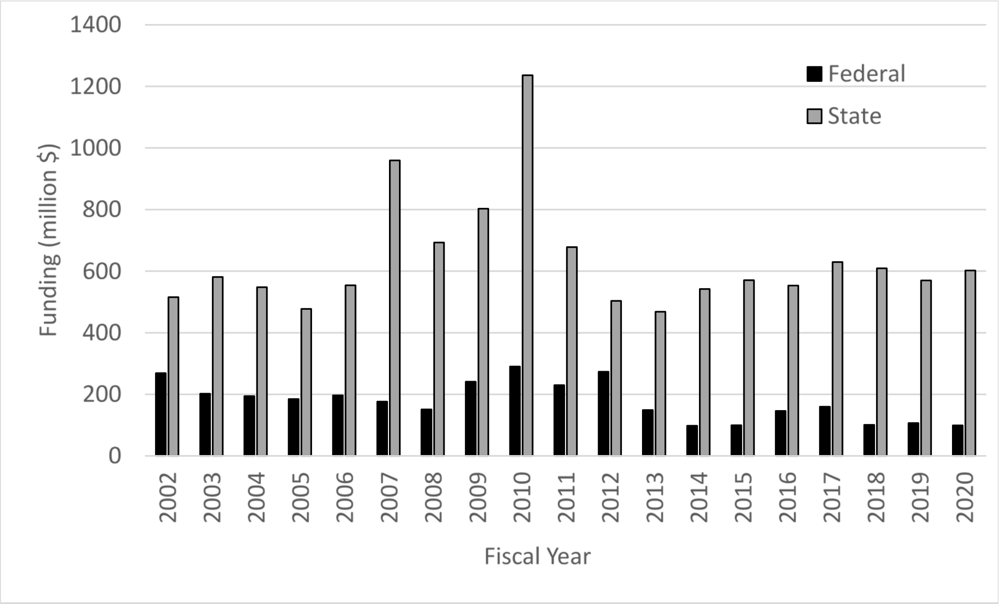

FIGURE 3-2 Federal and state funding for non-CERP restoration projects. SOURCE: Data from SFERTF, 2021.

Project Scheduling and Prioritization

The anticipated future progress of CERP projects and the relationships among all the federally funded South Florida ecosystem restoration projects and some highly relevant, state-funded projects are depicted in the Integrated Delivery Schedule (IDS). The Integrated Delivery Schedule is not an action or decision document but rather a communication tool across agencies that provides information to decision makers to guide planning, design, construction sequencing, and budgeting. The schedule is developed by the USACE and the South Florida Water Management District (SFWMD) in consultation with the Department of the Interior, the South Florida Ecosystem Restoration Task Force, and the many CERP constituencies. The IDS replaced the Master Implementation Sequencing Plan, initially developed for the CERP, as required by the Programmatic Regulations (33 CFR §385.31).

Updated versions of the IDS were released in October 2019 (USACE, 2019a) and October 2020 (USACE 2020c). The 2019 IDS was the focus of the committee's analysis based on the release of the 2020 IDS late in the review process, but many of the issues discussed here remain relevant to the 2020 IDS. The reporting horizon for the 2019 and 2020 schedules remains only through 2030 as in the previous July 2018 IDS. The most significant programmatic change compared to the 2018 IDS was an expanded and more detailed depiction of the CEPP that includes the EAA Storage Reservoir authorized in WRDA 2018. The expanded CEPP depiction is broken into three components: CEPP South, which removes barriers to flow in the southern half of the remnant Everglades; CEPP North, which addresses barriers to flow in northern Water Conservation Area 3A (WCA-3A); and CEPP New Water, which provides increased water storage and treatment to facilitate increased flows into the Everglades. An updated status of project implementation as of August 2020 is shown in Table 3-1, with expected completion dates based on the 2020 IDS.

Key limitations of the Integrated Delivery Schedule noted in NASEM (2016, 2018) remain in the 2019 IDS. First, it is difficult to discern individual project costs or essential dependencies among projects. Second, the IDS does not include the full set of anticipated CERP projects in the schedule—only project components scheduled through 2030—potentially providing a false impression of when CERP will be completed.[1] Third, although the Programmatic Regulations require RECOVER to assess any changes in the master schedule "for effects on achieving the goals and purposes of the Plan and the interim goals and targets," this is not being done. Communicating the effects of schedule changes on the nature and timing of anticipated ecosystem benefits could improve decision making, particularly in the context of current ecosystem trends and new pressures such as sea-level rise and harmful algal blooms, and potentially lead to shifts in priorities to maximize regional benefits.

Of greater concern, the October 2019 IDS notes: "The funding shown for FY20 and beyond is only notional, representing approximate funding levels that would be needed to sustain the work displayed in the IDS for a particular FY. The funding does not represent a commitment by the Administration to budget the amounts shown." This approach is a significant change from previous Integrated Delivery Schedules, which compounds the already false impression that the CERP will be completed in 2030. The October 2019 IDS indicates that $4.1 billion in total construction costs will be needed over the next 5 years (FY 2021-2025) or an average of $818 million per year. For comparison, the combined state and federal CERP funding averaged only $257 million per year over FY 2015-2019 and $344 million per year over FY 2016-2020 (Figure 3-1). This pattern suggests that realistic funding constraints could double or even triple the expected time frame for completing the projects currently included in the IDS.

In response to concerns expressed by the Task Force about the funding assumption underlying the October 2019 IDS, two additional hypothetical funding scenarios reflecting more realistic funding levels were presented at the May 7, 2020, Task Force meeting (Childress, 2020). These alternative scenarios illustrate how annual funding rates affect the pace of restoration.

An underlying assumption in the October 2019 IDS is that the rate of funding does not affect the optimal prioritization of projects. This assumption is maintained in the alternative funding scenarios (Childress, 2020). The validity of this assumption is questionable and its potential implications are a cause for concern. The rate of funding clearly determines the pace (time frame) of restoration. It is well understood that the system is continuing to degrade over time and that the rates of degradation vary across system components (NRC, 2012a). Some elements of the ecosystem are in poor condition but those elements could recover on relatively rapid time frames when improved conditions are provided (e.g., periphyton), while the degradation of other elements (e.g., peat loss) may not be recoverable on human time frames. Additionally, system inputs (e.g., temperature, rainfall) and boundary conditions (e.g., sea-level rise) are changing over time. All of which would argue that restoration benefits are likely time dependent and optimal project prioritization should reflect these dependencies.

If, in fact, optimal project prioritization is time dependent, then the 2019 IDS is misleading and inconsistent with the assertion that "the IDS synchronizes program and project priorities with the State of Florida and achieves the CERP restoration objectives at the earliest practicable time, *consistent with funding constraints* and the interdependencies between project components" (italics added). The IDS sidesteps the difficult but essential CERP interdependency scheduling decisions associated with realistic funding constraints. In the face of funding levels less than those identified in the current IDS, should all projects move forward simultaneously, but more slowly, or should some projects be prioritized over others to expedite benefits? The May 2020 alternative funding scenarios reflect a path of merely moving forward more slowly. Development of the IDS could serve as a means to debate these challenging decisions with the multiple CERP agencies and stakeholders. Uncertainty of funding (which occurs on regular basis) necessitates evaluation of realistic and alternative levels of funding with consideration of the many time-dependent factors that may affect an optimal project prioritization.

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[1] The 2020 IDS does include a list of all CERP projects and classifies them in the following categories: complete, authorized/design/construction, pending, planning/feasibility study, and deauthorized.

TABLE 3-1 CERP or CERP-Related Project Implementation Status as of June 2020

Project or Component Name	Yellow Book (1999) Estimated Completion	IDS 2020 Estimated Completion	Project Implementation Report Status	Authorization Status	Construction Status	Ecosystem Benefits Documented to Date
GENERATION 1 CERP PROJECTS						
Picayune Strand Restoration (Fig. 3-3, No. 2)	2005	2024	Submitted to Congress, 2005	Authorized in WRDA 2007	Ongoing	Increased water levels in 20,000 acres and with early vegetation responses detected
Site 1 Impoundment (Fig. 3-3, No. 3)	2007		Submitted to Congress, 2006	Authorized in WRDA 2007		
- Phase 1		Completed			Completed, 2016	~16% reduction in seepage loss
- Phase 2		Not specified		*Phase 2 requires further authorization*	Not begun	NA
Indian River Lagoon-South (Fig. 3-3, No. 4)			Submitted to Congress, 2004	Authorized in WRDA 2007		
- C-44 Reservoir/STA	2007	2021			Ongoing	None to date
- C-23/24 Reservoirs/STA	2010	2030			Not begun	NA
- C-25 Reservoir/STA	2010	2030			Not begun	NA
- Natural Lands	NA	Not specified			Not begun	NA
Melaleuca Eradication and Other Exotic Plants (Fig. 3-3, No. 5)	2011	NA	Final June 2010	Programmatic authority WRDA 2000	Construction completed 2013, operations ongoing	Increased capacity for biocontrol
GENERATION 2 CERP PROJECTS						
C-111 Spreader Canal Western Project (Fig. 3-3, No. 6)	2008	Not specified	Submitted to Congress, 2012	Authorized in WRRDA 2014	Mostly complete; S-198 structure not yet constructed.	Current data insufficient to assess response to project
Biscayne Bay Coastal Wetlands (Phase 1) (Fig. 3-3, No. 7)	2018	2024	Submitted to Congress, 2012	Authorized in WRRDA 2014	Ongoing	Some wetland vegetation responses to freshwater inputs
C-43 Basin Storage: West Basin Storage Reservoir (Fig. 3-3, No. 8)	2012	2023	Submitted to Congress, 2011	Authorized in WRRDA 2014	Ongoing	None to date, construction ongoing
Broward County WPAs (Fig. 3-3, No. 9)			Submitted to Congress, 2012	Authorized in WRRDA 2014		
- C-9 Impoundment	2007	After 2030			Not begun	NA
- C-11 Impoundment	2008	2027			Not begun	NA
- WCA-3A & -3B Levee Seepage Management	2008	2027			Not begun	NA
GENERATION 3 CERP PROJECTS						
Central Everglades Planning Project (Fig. 3-3, Nos. 10, 11, and 12)	NA		Submitted to Congress, 2015	Authorized in WRDA 2016, 2018		NA
- CEPP South		2027			Ongoing	
- CEPP North		2026			Not begun	
- CEPP New Water (incl. EAA Reservoir)		2027			Ongoing	

(Continued)

TABLE 3-1 Continued

Project or Component Name	Yellow Book (1999) Estimated Completion	IDS 2020 Estimated Completion	Project Implementation Report Status	Authorization Status	Construction Status	Ecosystem Benefits Documented to Date
GENERATION 4 CERP PROJECTS						
Loxahatchee River Watershed (Fig. 3-3, No. 13)	2013	Not specified	Submitted to Congress, 2020	Authorized in WRDA 2020	Not begun	NA
CERP PROJECTS IN PLANNING OR NOT YET AUTHORIZED						
Lake Okeechobee Watershed (Fig. 3-3, No. 14)	2009-2020	NA	Final PIR, Aug. 2020	NA	NA	NA
Western Everglades (Fig. 3-3, No.15)	2008-2016	NA	In development	NA	NA	NA
Biscayne Bay Southeastern Everglades Ecosystem (Figure 3-3, No.16)	2008-2020	NA	In development	NA	NA	NA
REMAINING UNPLANNED CERP PROJECTS						
WCA Decompartmentalization (Phase 2)	2019	NA	NA	NA	NA	NA
Everglades National Park Seepage Management	2013	NA	NA	NA	Partly addressed by LPA Seepage Management Project	NA
C-43 ASR	2012	NA	NA	NA	NA	NA
Site 1 Impoundment ASR	2014	NA	NA	NA	NA	NA
Palm Beach Agricultural Reserve Reservoir	2013	NA	NA	NA	NA	NA
Central Lake Belt Storage Area	2021-2036	NA	NA	NA	NA	NA
WCA-2B Flows to Everglades National Park	2018	NA	NA	NA	NA	NA
WPA Conveyance	2036	NA	NA	NA	NA	NA
Caloosahatchee Backpumping with Stormwater Treatment	2015	NA	NA	NA	NA	NA
A.R.M. Loxahatchee National Wildlife Refuge Internal Canal Structures	2003	NA	NA	NA	NA	NA
Broward Co. Secondary Canal System	2009	NA	NA	NA	NA	NA
Henderson Creek – Belle Meade Restoration	2005	NA	SW Florida Comprehensive Watershed Plan, 2015	NA	NA	NA
Southern CREW	2005	NA	NA	NA	NA	NA
Florida Bay Florida Keys Feasibility Study	2004	NA	Study terminated in 2009	NA	NA	NA
Comprehensive Integrated Water Quality Plan	2006	NA	NA	NA	NA	NA

NOTES: Table 3-1 does not include non-CERP foundation projects. NA = not applicable. Remaining unplanned CERP projects include all projects more than $5 million (2014 dollars) as reported in USACE and DOI (2016), for which the components have not been incorporated in other planning efforts. Lake Trafford Restoration has been removed from the CERP and will be completed by the SFWMD.
SOURCES: NASEM, 2018; USACE, 2020c, E. Velez, USACE, personal communication, 2020; N. Hooseinny-Nabibaksh, SFWMD, personal communication, 2020.

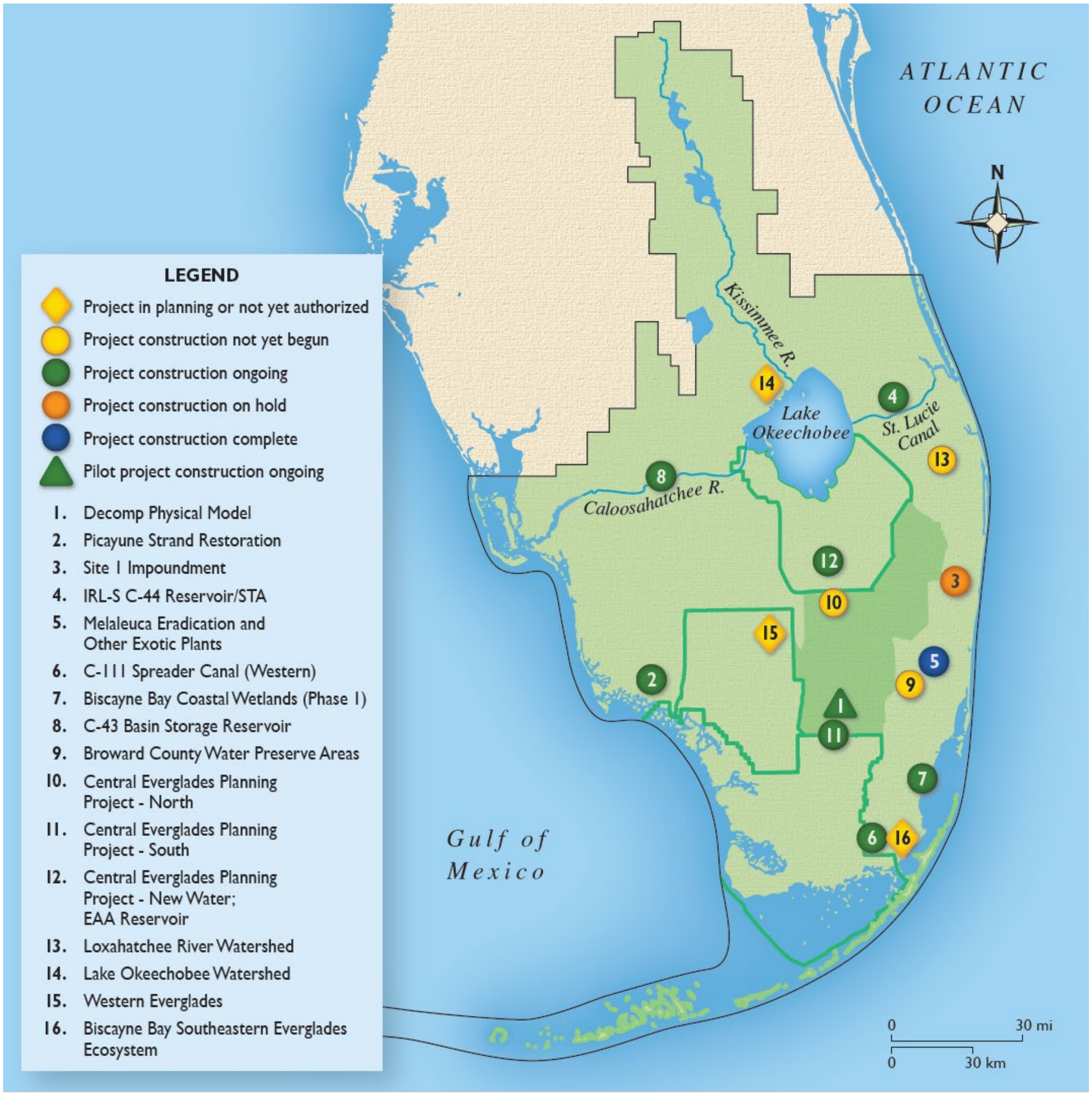

FIGURE 3-3 Locations and status of CERP projects and pilot projects. SOURCE: International Mapping Associates. Reprinted with permission; copyright 2021, International Mapping Associates.

NATURAL SYSTEM RESTORATION PROGRESS

In the following sections, the committee focuses on recent information on natural system restoration benefits emerging from the implementation of CERP and major non-CERP projects. The discussions of progress that follow are organized based on geography and describe CERP projects, non-CERP projects, and CERP projects in planning for:

- Central and western Everglades,
- Lake Okeechobee and the northern estuaries, and
- The southern estuaries

The findings and conclusions are based on reported monitoring data to date for CERP projects for which construction has begun, with emphasis on progress and new information gained in the past 2 years. The committee's previous report (NASEM, 2018) contains additional descriptions of the projects and progress up to July 2018. The South Florida Environmental Report (SFWMD, 2020) and the 2018 Integrated Financial Plan (SFERTF, 2018) also provide detailed information about implementation and restoration progress. Following these regionally based discussions, the committee reviews systemwide evaluation of the state of the South Florida ecosystem.

Central and Western Everglades: CERP Projects

This section includes CERP projects with sufficient construction progress that they are affecting remnant Everglades and western Everglades, located south of Lake Okeechobee. These projects include the C-111 Spreader Canal (Western) Project, Picayune Strand Restoration Project, the Melaleuca Eradication Project, and the Site 1 Impoundment. Early construction progress on the CEPP is also briefly discussed.

C-111 Spreader Canal (Western) Project

The C-111 Canal (Figure 3-3, No. 6) is the southernmost canal for the entire Central and Southern Florida (C&SF) Project. The canal system (Figure 3-4) was engineered in the 1960s, expanding upon a remnant canal designed to transport solid fuel moon rockets from the AeroJet General Corporation. Originally designed to provide flood protection in Dade County, the C-111 Canal spurred agricultural development on lands to the east while draining water from the Southern Glades and Taylor Slough in Everglades National Park. A principal source of the freshwater in the canal is seepage from

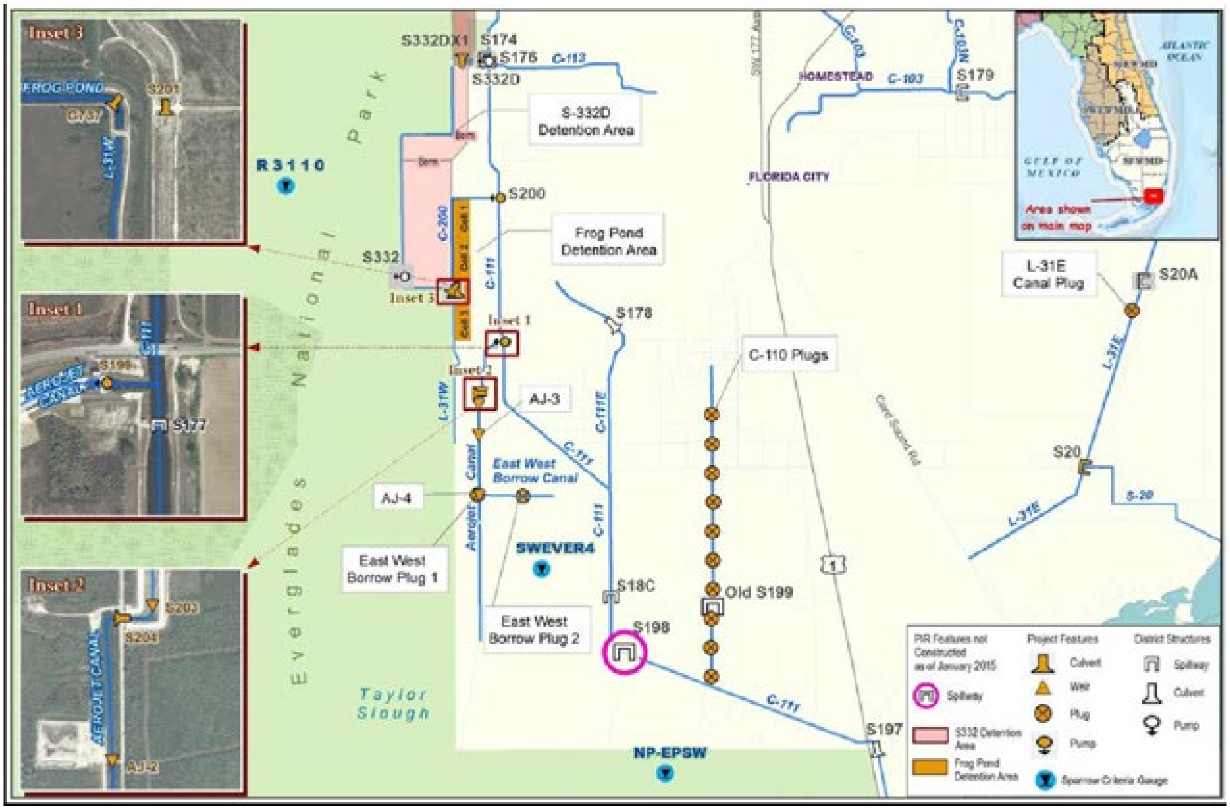

FIGURE 3-4 C-111 Spreader Canal Western Project features. SOURCE: Qui et al., 2018.

Everglades National Park. Because seepage drains water from the park and alters the flow pattern of Taylor Slough, it has potentially deleterious ecological and environmental effects on Taylor Slough and Florida Bay. The C-111 Canal also discharges large volumes of freshwater through the S-197 structure into Manatee Bay and Barnes Sound, while reducing overland flows that entered the central zone of Florida Bay, altering the natural salinity regime and ecology of those waters (see also Chapter 5).

The construction of the C-111 Spreader Canal project was envisioned in two phases—the western and eastern projects. The C-111 Spreader Canal (Western) Project, working in concert with the non-CERP C-111 South Dade Project and the SFWMD Florida Bay Initiative to the north, was designed to retain water in Taylor Slough and improve the quantity, distribution, and timing of flow into eastern Florida Bay (USACE and SFWMD, 2011a). The project creates a 6-mile-long hydraulic ridge along the eastern boundary of Everglades National Park to reduce seepage from the park and improve the hydrology of Taylor Slough. The project also includes canal modifications to reduce canal flows into eastern Florida Bay. To create this hydraulic ridge, excess canal water is pumped into the Frog Pond Detention Area through S-200 (see Figure 3-4) and the Aerojet Canal impoundment (through S-199) to the west of the canal. This water will seep into the ground and later flow back into the canal. However, the hydrologic ridge element only functions when water is available to fill the detention areas. The project was largely completed in February 2012 and operations began in June 2012. One major authorized component—the S-198 structure in the lower section of the C-111 canal—remains to be completed. According to the 2020 IDS, this last component is to be completed by 2025 (USACE, 2018b). Planning for the second project, the C-111 Spreader Canal Eastern Project, began in mid-2020 as part of the Biscayne Bay-Southern Everglades Ecosystem Restoration (BBSEER) project (USACE and SFWMD, 2020b).

In its last report (NASEM, 2018), the committee discussed the difficulty in assessing progress from this project due to the lack of rigorous analysis of monitoring data, considering interannual variability in precipitation and expected performance. These challenges continue, and the committee was unable to obtain new data analyses that resolved these issues, even when examining the collective response of the multiple CERP and non-CERP projects in this region. Some data highlight potential positive trends with the onset of the project related to water levels and salinity in coastal lakes. For example, in West Lake, at the western edge of Taylor Slough, the cover of *Chara*, a desirable microalgae, has increased, and it appears that spikes in salinity in the coastal lakes in the same region have decreased in severity since 2012 (Figure 3-5). However, without more rigorous trend analysis across the system it is difficult to draw definitive conclusions about the benefits of the project at this time, particularly given interannual variation in precipitation. This conclusion is consistent with the findings from NASEM (2018). High variability, natural and confounding factors (sea-level rise, changes in weather), and the effects of nearby non-CERP projects (e.g., C-111 South Dade [see Chapter 4]) continue to make it difficult to effectively quantify the benefits of this CERP project on Florida Bay. These issues point out the need to evaluate monitoring programs and study designs through rigorous assessments to evaluate if they are able to establish restoration progress with known certainty. This need is especially important when monitoring plans change due to reductions in budget.

Picayune Strand Restoration

The Picayune Strand Restoration Project, the first CERP project under construction, focuses on an area in southwest Florida substantially disrupted by a real estate development project that drained 55,000 acres (about 86 mi^2) of wetlands before being abandoned (Figure 3-3, No. 2). The roads and drainage disrupted sheet flow into Ten Thousand Islands National Wildlife Refuge, altered regional groundwater flows in surrounding natural areas, and drained a large expanse of wetland habitat (Figure 3-6).

The primary objective of the Picayune Strand Restoration Project is to "establish the pre-development hydrologic regime, including wet and dry season water levels, overland sheet flow, and hydroperiod" (RECOVER, 2014). An array of ecological objectives is dependent on the restoration of hydrology. Hydrologic restoration involves filling at least 50 percent of the length of the larger canals and several smaller ditches draining the area. The project also requires eliminating impediments to

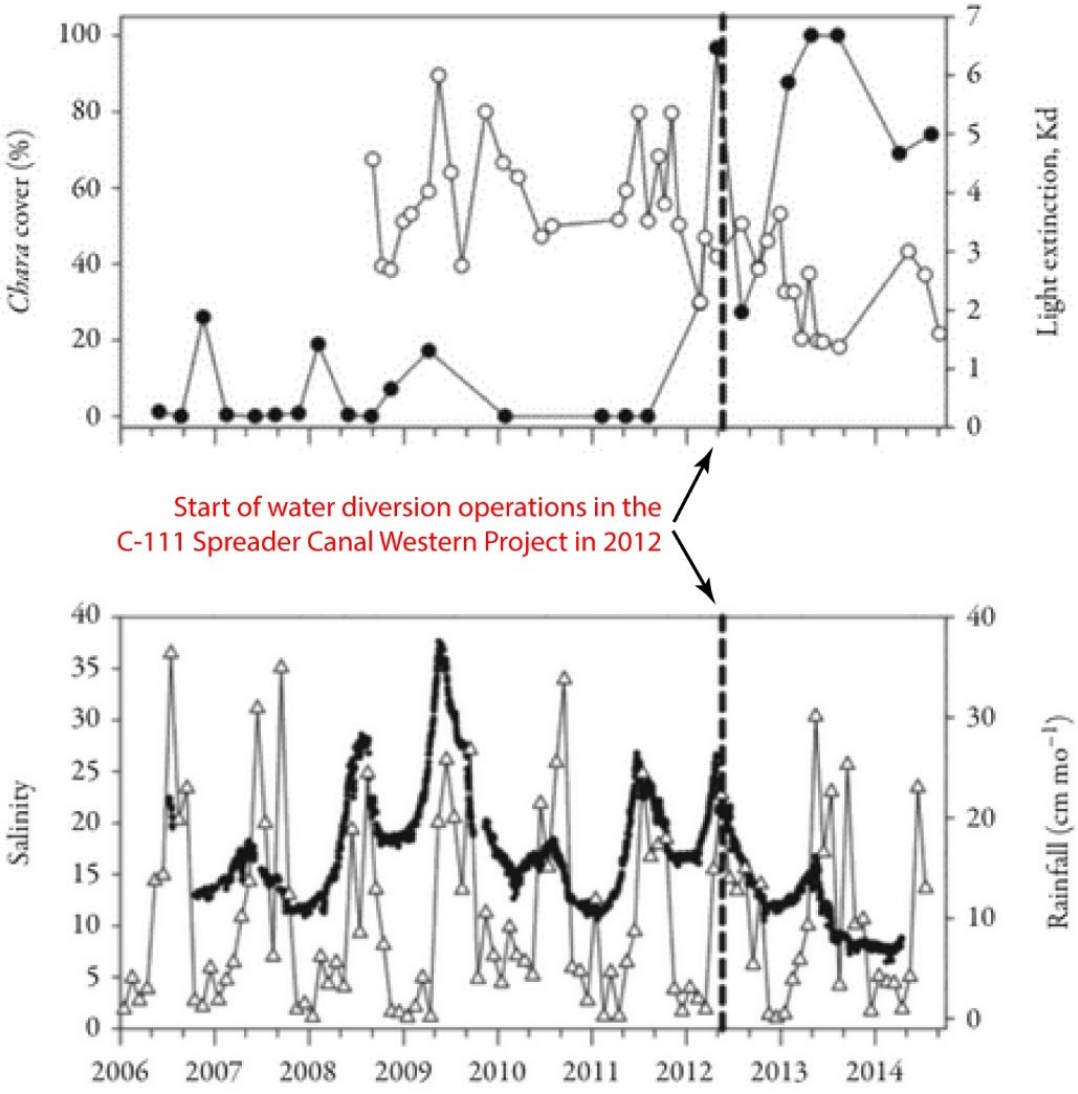

FIGURE 3-5 Top: Time series of *Chara* cover (solid circles), a desirable macroalgae and water column light extinction (K_d, open circles). Bottom: Salinity (solid circles) and rainfall (open triangles) in West Lake, located west of Taylor Slough. Rainfall data are monthly sums from NEXRAD data for North Cuthbert Lake from the U.S. National Weather Service. Vertical lines indicate the start of water diversion operations in the C-111 Spreader Canal Western Project in 2012. Increases in *Chara* cover and reduced salinities are coincident with initiation of the C-111 Spreader Canal Project. SOURCE: Sklar et al., 2019. Reprinted with permission; copyright 2019, Oxford University Press.

reestablishing sheet flow by removing more than 250 miles of raised roads and logging trams and plugging more than 40 miles of canals. There has been considerable progress in constructing the Picayune Strand Restoration Project, including canal plugging, road removal, and construction of pump stations, although it was necessary to add features to maintain flood protection to neighboring developed areas, which extended the time frame for project completion (Table 3-2). The ecosystem responses expected to arise from hydrologic restoration include the reestablishment of natural plant distribution and composition, increase in fish and wildlife resources, improved habitat for listed species, and greater ecological connectivity to adjacent public lands (USACE and SFWMD, 2004a). To achieve these

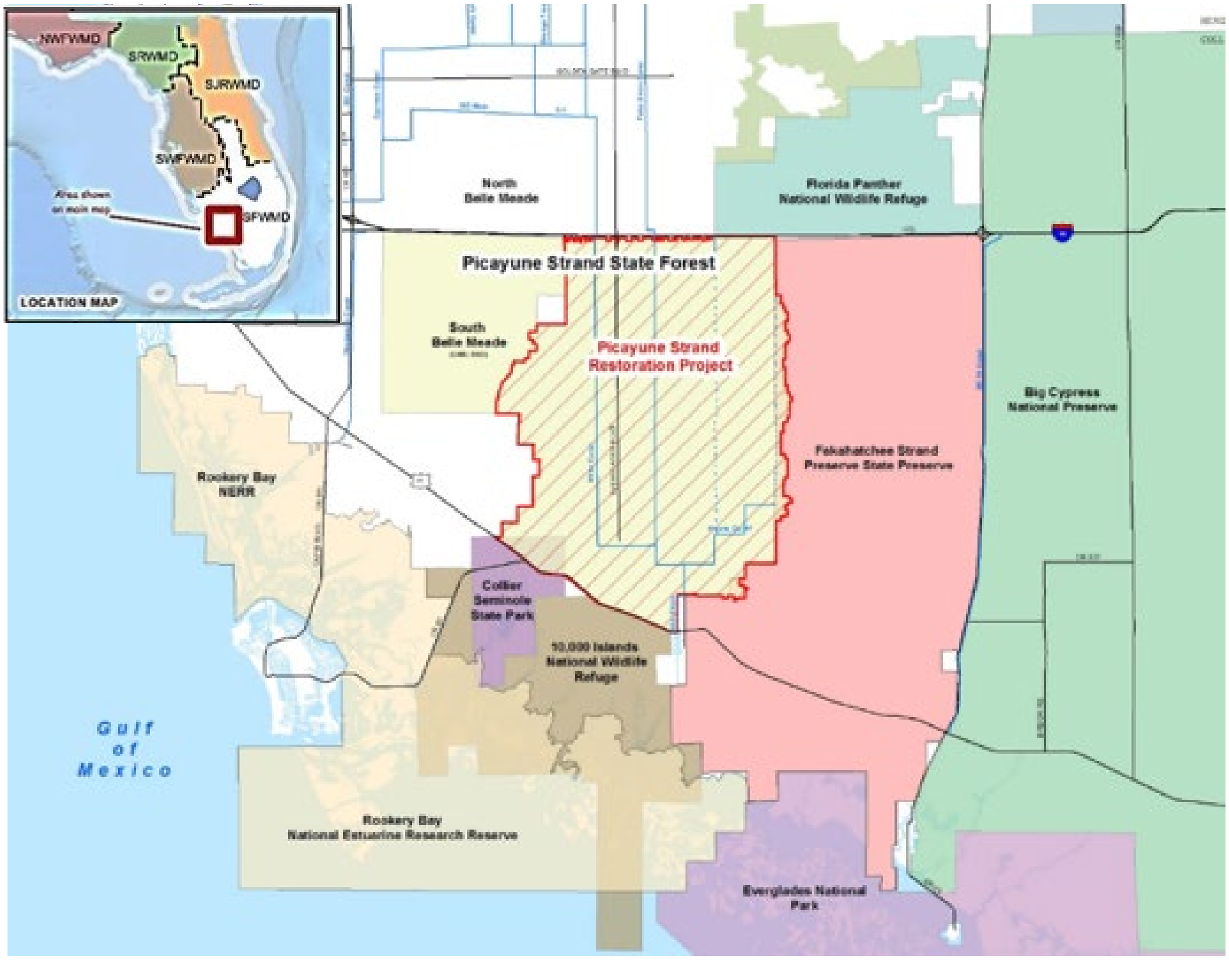

FIGURE 3-6 The Picayune Strand Restoration Project area is surrounded by several other natural areas, including Collier-Seminole State Park, Ten Thousand Islands National Wildlife Refuge, Picayune Strand State Forest, Fakahatchee Strand Preserve State Park, and Florida Panther National Wildlife Refuge. Restoration of water levels within the project footprint will enhance the hydrologic conditions in these surrounding natural areas. SOURCE: Chuirazzi et al., 2018.

benefits, the project requires not only the restoration of natural hydropatterns, but also the control of exotic, invasive, and nuisance plants and reestablishment of a natural fire regime in the Picayune Strand State Forest. The project is also expected to improve estuarine conditions in the Ten Thousand Islands region by reducing canal discharges to Faka Union Bay and increasing freshwater flows to Blackwater Bay and Pumpkin Bay (USACE and SFWMD, 2004a).

Because hydrologic restoration is a prerequisite for ecological restoration, hydrologic monitoring should provide the first signals of restoration progress. A robust monitoring effort for both hydrologic and ecological objectives (USACE and SFWMD, 2009) was established in 2009, although the monitoring plan was reduced in 2014 as part of budget reductions (M. Duever, Natural Ecosystems, personal communication, 2020). Currently, the hydrologic monitoring has delineated the project area into three levels of hydrologic restoration achieved to date—full, partial, and no hydrologic restoration—determined based on the project components constructed and the local influences of neighboring canals on water levels (see Figure 3-7). Since construction has begun, ecological monitoring has been focused on areas with full or partial hydrologic restoration, utilizing reference sites in neighboring Fakahatchee Strand

TABLE 3-2 Phases and Progress of the Picayune Strand Project

	Lead Agency	Road Removal (mi)	Logging Tram Removal	Canals to Be Plugged (mi)	Other	Project Phase Status
Tamiami Trail Culverts	State	NA		NA	17 culverts constructed	Completed in 2007
Prairie Canal Phase	State (expe-dited)	64	30	7	Hydrologic restoration of 11,000 acres in Picayune Strand and 9,000 acres in Fakahatchee Strand State Preserve Park	Plugging and road removal completed in 2007; logging trams removed in 2012
Merritt Canal Phase	Federal	65	16	8.5	Merritt pump station, spreader basin, and tie-back levee constructed	Completed in 2015; pump station transferred to SFWMD in 2016
Faka Union Canal Phase	Federal	81	11	7.6	Faka Union pump station, spreader basin, and tie-back levee constructed	Roads removed in 2013; pump station completed in 2017; upper 3 miles canal plugging scheduled for 2021. The rest is scheduled for 2025
Miller Canal Phase	Federal/state	77	11	13	Construct pump station, spreader basin, tie-back levee, and private lands drainage canal; remove western stair-step canals	Miller pump station completed June 2019; road removal and canal plugging TBD, respectively
Manatee Mitigation Feature	State	0	0	0	Construct warm water refugium to mitigate habitat loss	Completed in 2016
Southwestern Protection Feature	Federal	0	0	0	Construct 7-mile levee for flood protection of adjacent lands	Construction completion scheduled for 2024
Eastern Stair-step canals	Federal	0	0	5.2		Plugging completion expected in 2021

SOURCE: J. Starnes, SFWMD, personal communication, 2016; Chuirazzi et al., 2020; J. Weaver, SFWMD, personal communication, 2020.

Preserve State Park and Florida Panther National Wildlife Refuge (Barry et al., 2017, 2019; Worley et al., 2017).

Hydrologic restoration progress. Patterns of lengthening hydroperiod (days per year that water levels are at or above ground surface) appear to follow restoration progress, with the largest gains demonstrated at wells in the fully restored areas. For example, it appears that there has been a lengthening hydroperiod in the upper reach of the Prairie Canal (Well 10 in Figure 3-7) almost immediately after plugging the Prairie Canal (2004 through 2007) and further lengthening after the filling of the neighboring Merritt Canal in 2015, when the area was considered to be fully restored (Figures 3-8 and 3-9). Records from this area for 1997-2004 indicated a lack of recorded standing water, in contrast to the significant hydroperiods observed in 2008, 2013, and the fall and winters of 2015 through 2020. A partially restored area along the Merritt Canal (Well 8 in Figure 3-7) appears to be responding to the canal plugging and removal of roads and logging trams completed in 2015 (Figure 3-10). This area had no significant periods of inundation until 2015 and 2016, in which the completion of restoration activities coincided with above average rainfall years.

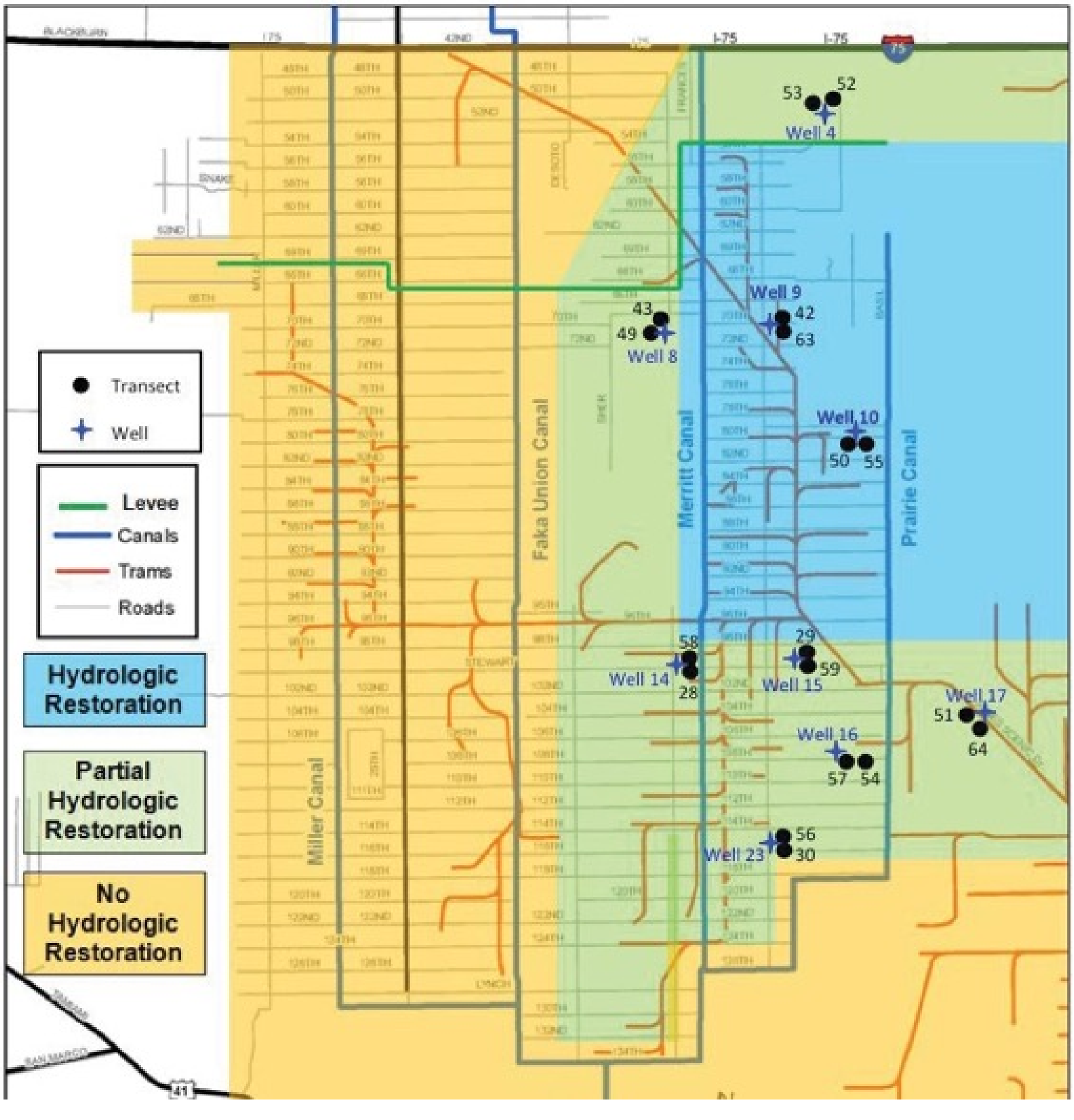

FIGURE 3-7 Schematic illustration of hydrologic restoration at Picayune Strand with locations of vegetation monitoring transects and monitoring wells for the 2016 sampling event. SOURCE: Chuirazzi et al., 2018.

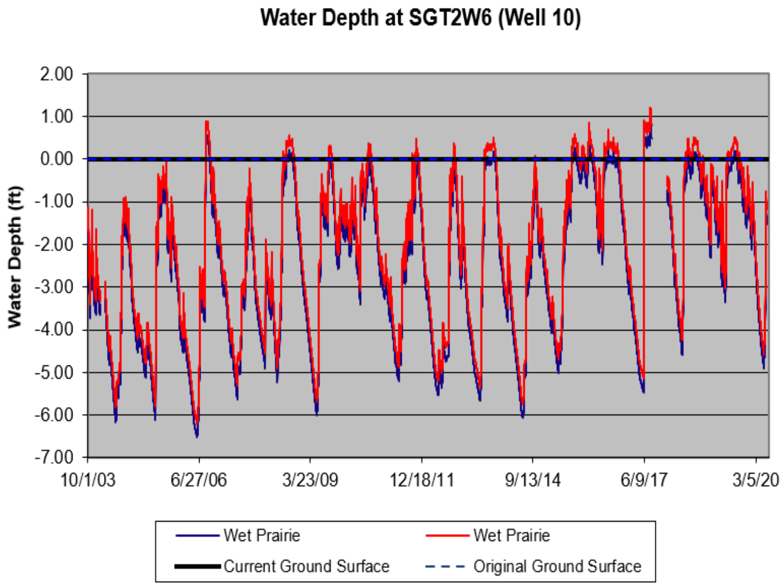

FIGURE 3-8 Groundwater depth at the Prairie Canal, which achieved partial hydrologic restoration in 2004 and 2007 and full hydrologic restoration in 2015. The red and blue lines represent two wet prairie vegetation sampling sites near Well 10. Gap in data in 2017 due to Hurricane Irma. SOURCE: M. Duever, personal communication, 2020. Reprinted with permission; copyright 2020, M. Duever.

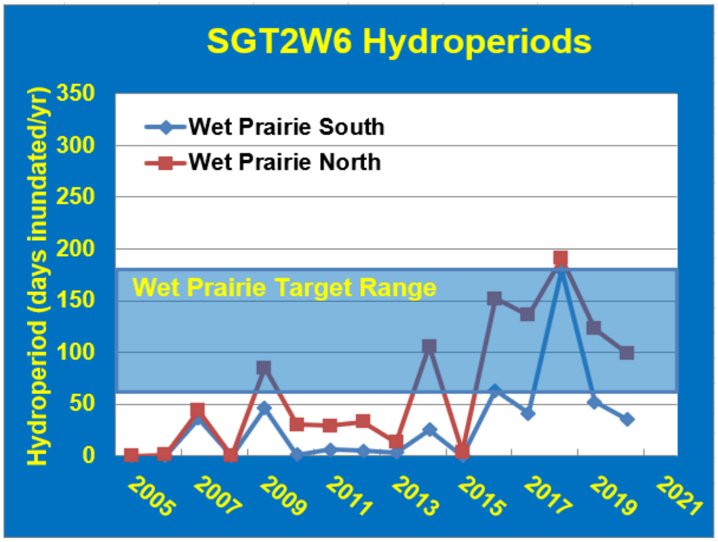

FIGURE 3-9 Hydroperiods (nonconsecutive days inundated per year) for wet prairie locations in two transects near Well 10 (fully restored area) for the water years 2005 through 2020, along with targets. Plugging the Merritt Canal in 2015 led to consistent increases in hydroperiod. SOURCE: M. Duever, personal communication, 2020. Reprinted with permission; copyright 2020, M. Duever.

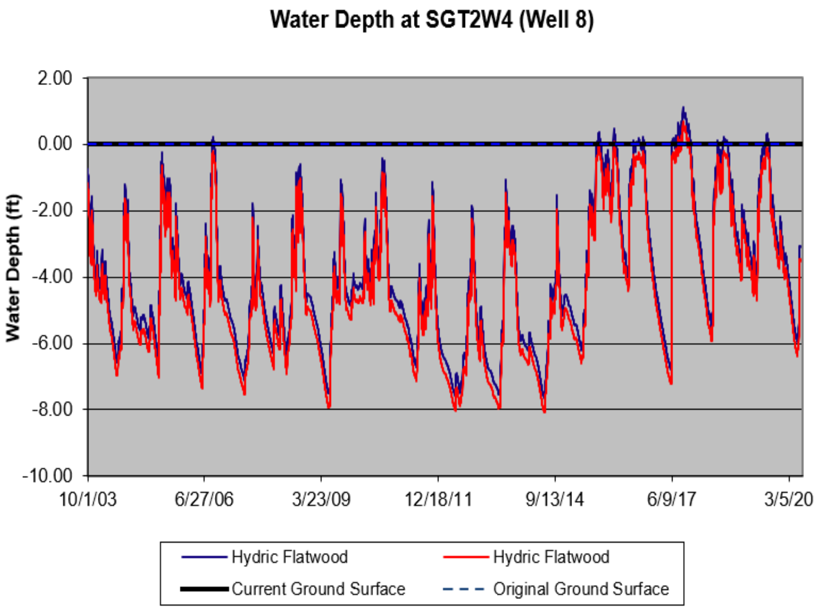

FIGURE 3-10 Groundwater depth at the Merritt Canal, which achieved partial hydrologic restoration in 2015. The red and blue lines represent two hydric flatwood vegetation sampling sites near Well 8. SOURCE: M. Duever, personal communication, 2020. Reprinted with permission; copyright 2020, M. Duever.

Reports of improvement have been visual and not evaluated quantitatively against expectations from models (considering factors such as timing and distribution of rainfall, temperature, wind, humidity, evapotranspiration rates, as well as changes in vegetation). Hydroperiod targets are available for primary plant communities and it is expected that Picayune Strand restoration will increase hydroperiods in these communities. Estimation of hydroperiods in two vegetation transects near Well 10 suggests that since 2015 there have been improvements in hydroperiods for hydric flatwood and wet prairie communities (although recent data suggest the targets were not met in the southern region) (Figure 3-9). As restoration proceeds and the eastern stairstep canals are plugged, it is expected that hydroperiods will increase further in this area. These early indicators of restoration progress could be easily communicated to the public through simple metrics and figures; by not communicating these metrics more broadly, the CERP is missing an opportunity to highlight the progress made.

Ecological restoration progress. The monitoring of flora and fauna also suggests some ecological improvements in the restored areas. Restoration work began in 2004, and 63 vegetation transects were established in 2005 to assess restoration progress. These transects have been irregularly sampled six additional times since 2005. The most recent vegetation monitoring analysis (Barry et al., 2019) used data through 2018 from 18 of these transects located in the restored areas (and 9 control transects) to describe results for vegetation transects in three types of predrainage habitat—cypress, wet prairie, and pineland—which are reported by four strata (i.e., vertical layers of vegetation): canopy trees, subcanopy trees, the shrub layer, and groundcover.[2] Their report summarized vegetation monitoring data using vegetation indices, multivariate ordination methods and observations.

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[2] Canopy trees consist of woody plants with a diameter at breast height (dbh) greater than 10 cm; subcanopy trees consist of woody plants with a dbh between 2.5 and 10 cm, excluding woody shrubs; the shrub layer consists of trees with a dbh of less than 2.5 cm and all shrub individuals; and groundcover consists of all remaining plants and primarily herbaceous species.

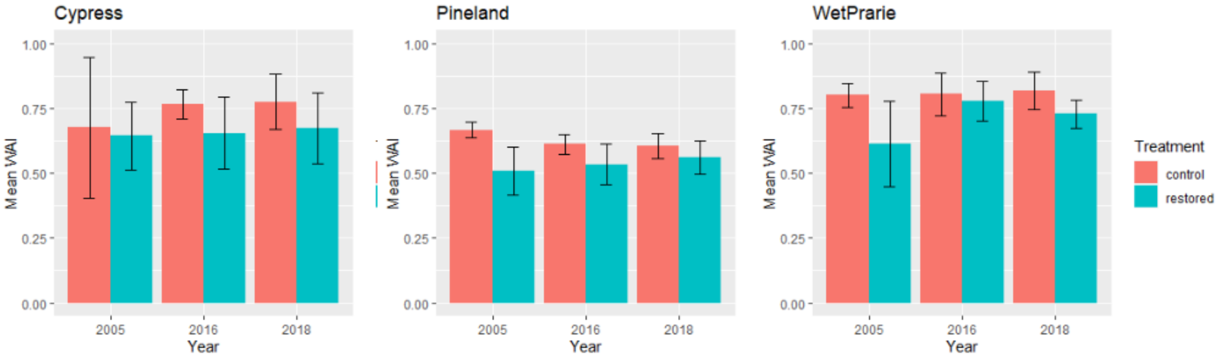

FIGURE 3-11 Groundcover wetland affinity index comparison of 2005, 2016, and 2018. Marsh and hammock habitat types were not included because of data limitations. Mean plus or minus standard deviation. Sample sizes are 3 for control, 8 for cypress restored, 4 for pineland restored, and 4 for wet prairie restored. NOTE: "Control" here describes the reference sites. SOURCE: Data from Barry et al., 2019.

The vegetation monitoring results provide an emerging trajectory of restoration, although few definitive conclusions can be drawn from the data. Across all habitat types, short-term changes are most evident in the groundcover stratum, as should be expected. Comparisons of the groundcover in the wet prairie habitat between 2005, 2016, and 2018 show evidence of recovery toward typical wetland vegetation. One index used to summarize vegetation change is the wetland affinity index (WAI),[3] which represents an artificial index of dominance by hydrophytic (inundation-tolerant) vegetation species, over three different habitat types. By 2016, WAI averages in wet prairie transects became more similar to reference transects, which represent the target restoration conditions (Figure 3-11). Mean WAI values in restored transects in pinelands have increased only slightly and are closer to the reference mean WAI but have not increased much since 2005. A possible reason for the small increase is that the restored transects occur in areas with partially restored hydrology. In addition, the pinelands have the highest elevations, so hydrologic changes would not be expected to result in significant changes. As expected because of the slow growth of cypress, cypress habitats show little improvement; cypress habitats could take decades to show a significant response. Indices such as WAI are generalizations of the vegetation community as data from a number of species are combined. The index may ignore the importance of critical species or the actual composition of species.

Other summaries and analysis by Barry et al. (2019) indicate the importance of controlled fire that removes overgrowth of shrubs and reduces cabbage palm seedling recruitment and survival. The cabbage palm is the key invasive species because drainage created conditions that enabled it to establish, and restoration of hydrology will not eliminate it. Increased inundation in wet prairie habitat may be responsible for reductions in the invasive Brazilian pepper density in one transect and favorable changes in wetland species in another transect.

Monitoring data from 2016 and 2018 for faunal indicators (e.g., treefrogs, aquatic macroinvertebrates, and fish) show a system that is generally in transition from short hydroperiods to more sustained surface water inundation. However, there is high variability among individual sites and over time (Ceilley et al., 2020; Worley et al., 2017), which makes identification of significant differences between restored, partially restored, and nonrestored sites more difficult to detect using the faunal indicators. Macroinvertebrate data, for example, were evaluated using multivariate analysis and indices such as species richness, evenness, and diversity indices. Although there is some indication of improvements in some restored sites (i.e., grasses and cypress) associated with hydroperiod restoration,

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[3] The wetland affinity index is calculated as the probability that an observed species generally occurs within wetlands times the relative frequency of occurrence, summed over the species detected in the quadrant or transect.

high variability and adverse environmental conditions (a shortened hydroperiod and dry October sampling sites) weakened inferences for other groups of sites (Ceilley et al., 2020).

Invasive species continue to be a problem in Picayune Strand and there is an ongoing effort to map the extent of invasive species and control their expansion (Barry et al., 2017). The recent survey was reduced in scope due to lack of funding (Barry, 2019). More than 100 invasive species have been documented and 64 mapped, and the results show that management success has been mixed. Although some invasives have been partially controlled, torpedograss and cattail increased steadily in both the Prairie and Merritt Canal Phases because of an inability to treat these species due to weather and budget constraints (Barry, 2019). It is expected that increased inundation will reduce these invasives. Woody plants such as Brazilian pepper and cabbage palm continue to be problematic.

The aquatic fauna monitoring data provide striking evidence of the challenges from invasive species on understanding ecological responses to restoration. For example, there was no statistically significant difference in treefrog composition between reference and restored sites largely because the exotic Cuban treefrog is outcompeting native species across all sites. Fish composition showed a similar challenge, with the postrestoration study documenting the presence of the non-native African jewelfish across both reference and restored sites; the species was not present in baseline studies.

Effects of fire management on restoration progress. Fire, as either controlled burns or wildfire, is an important factor determining understory vegetation. Barry et al. (2019) considered controlled burns to be as important as hydrologic restoration. In pinelands, for example, fire is necessary to control the growth of shrubs and provide opportunity for germination and growth of pine. Prior to restoration, drainage resulted in drier habitats that were significantly affected by wildfires, and the combination of drainage and fire increased the spread of fire-tolerant invasive species, such as cabbage palm and Brazilian pepper (Barry et al., 2019). Controlled burns are especially important in these areas to help limit the germination and growth of invasive species. Barry et al. (2019) indicated that the reference transects (i.e., target conditions) experience greater fire frequency, which reduces cabbage palm seedling success and understory shrubs. Various metrics associated with fire events are not routinely recorded and maintained in a database (with the exception of Florida Panther National Wildlife Refuge) because of lack of systematic reporting by the fire management agencies even though these data are critical for interpretation of changes in vegetation. Fires also affect the monitoring of restoration response, including destruction of sampling devices and harm to vegetation from vehicles and control procedures. Transects with different fire histories will also show different vegetative responses.

Issues and opportunities with monitoring and evaluation of success. Reports and discussion from those evaluating monitoring data raise a number of concerns about the monitoring programs and their continuity (examples provided in Table 3-3; see also Ceilley et al., 2020). As currently designed, there is little evidence that restoration success can be determined with any certainty for indicators beyond hydroperiod. Several improvements to the ecological monitoring program would enhance evaluations of restoration progress and better support adaptive management. NASEM (2018) also discussed improved monitoring and assessment strategies to more rigorously demonstrate early restoration success.

First is the need for clearer monitoring objectives (see NASEM, 2018). Although the objective of the monitoring appears to be to provide statistical evidence of restoration success, few statistically significant responses to restoration have been documented, and for several metrics, invasive species and natural events (e.g., fire, drought) are confounding meaningful assessments. If statistical evidence of success is the goal, the monitoring plan should be reviewed to assess whether the number of sampling units, metrics, and frequency of monitoring are appropriate to provide this information, particularly within a partially restored system. The current sample sizes generally are rather small for the analyses that are considered, resulting in low power for statistical tests (a large difference is required for statistical significance). There is also considerable variation between sampling sites within the control and restored groups. Therefore, strategies should be developed to reduce variability in the sampling and measurement process. Possible actions include using experienced staff to plan and conduct the monitoring, especially where sampling technique or sample processing is likely to affect data quality. Faunal sampling methods may need to be refined to minimize bias associated with differential detection probabilities or identification of organisms (Jacobsen and Kushland, 1987; Michelangeli et al., 2016; Parkos et al., 2019). Agencies should be cognizant of other factors that may exacerbate variability, such as differences in fire history or invasive species treatment among transects, and include this information in databases. If other sources of variability, such as invasive species, are so large that monitoring no longer provides meaningful information about restoration progress, some components of the ecological monitoring plan may need to be eliminated.

If decision makers expect monitoring to inform future management decisions, adaptive management should be emphasized as a monitoring objective, with management questions identified so that monitoring and assessment can be targeted to address the questions. For example, managers may want to understand the impacts of invasive species on CERP restoration goals at Picayune Strand. Cabbage palm, which was established when Picayune Strand was drained, is a key invasive species in the area and neither simple fire nor hydrologic restoration will eliminate it. The adaptive management plan (USACE, 2014) suggests selective harvesting of cabbage palm and management through controlled burn. Monitoring and modeling can help identify and track critical cabbage palm management areas that affect restoration goals and be used to examine the effectiveness of practices to remove or reduce the density of palms. Metrics used in the analyses would need to be coordinated with objectives. For example, the WAI is useful as a general summary of wetland vegetation, but it does not track species-specific goals. In cypress habitat, for example, it is possible to obtain good WAI values without having any cypress present.

Second, improved analysis and modeling both before and after sampling would improve the usefulness of the data collected (NASEM, 2018). The complexity of the modeling that has been used is varied across research reports. In some cases, simple tests are used to compare control and restored sites. In other analyses, a more complex multivariate approach is used. Ideally there should be an *a priori* plan that specifies what might be expected and what is biologically important, and a discussion of analyses and hypotheses that reflect the biological expectation (i.e., the alternative hypothesis might be one sided, increasing the power of the test). In the Picayune Strand monitoring plan (USACE and SFWMD, 2009), however, expectations for restoration success are not defined. Finally, there is no plan with regard to how to incorporate fire and rainfall into the analysis. Although fire events are recorded for the monitoring transects, the incidence of fire is not included in modeling of the data. Inclusion would require a more complex model for analysis, but such an analysis is possible and would improve the utility of results.

Third, there is a need is for better communication and planning across different agencies, especially related to prescribed burns. Prescribed burning is the responsibility of the Florida Forest Service and is necessary to control invasive vegetation, eliminate buildup of natural fuel sources, and support natural vegetation processes (Barry et al., 2019). Burning at a schedule that is similar to reference sites is required to support restoration, especially in the pinelands. If vegetation monitoring is critical, then the agency involved in prescribed burns needs to recognize this importance, work with other agencies, and inform monitoring personnel about the location and timing of the burn. Efforts should be made to avoid, to the extent possible, damaging the natural, desirable vegetation as well as the monitoring equipment both from the burn and from equipment used in fire management. Improved reporting on the timing and spatial extent of controlled burns can lead to better modeling and evaluation of the restoration process and improve adaptive management.

Finally, adequate and consistent funding is required for effective monitoring and adaptive management. Unplanned monitoring funding cuts can lead to reductions in data quality (e.g., if using interns instead of more experienced staff) or data gaps that limit the knowledge gained from this long-term investment. For example, taxonomic identification is dependent on factors such as the skill of the researcher, and changes in budget and researchers in different years can therefore affect identification and inference about changes in taxonomic composition over time (Ceilley et al., 2020). These effects can be limited through careful longer-term planning that considers the value of the information gained from the different monitoring investments and examines ways to address critical questions with less cost (see NASEM, 2018). Recent expectations for quality assurance and quality control in contracts from the Florida Department of Environmental Protection and SFWMD may improve the consistency and value of information collected (FDEP, 2018).

Monitoring to inform management decisions. There is a great opportunity to revise and implement a monitoring plan that can be used for improving management actions rather than simply documenting changes in the Picayune Strand Restoration Project. Although there is a comprehensive adaptive management plan for the project (USACE, 2014), the plan has not yet been used to inform management changes. The challenges faced in Picayune Strand are significant and could be usefully addressed through an adaptive management plan targeted toward the most critical decisions. For example, restoration projects rarely restore an area to historical conditions (Duarte et al., 2009; Livingston, 2006). Improving hydrology improves conditions for desirable flora and fauna but also provides opportunities for invasive species, which are sometimes difficult to control (Barry, 2019). Although prescribed burns may be effective at reducing invasive vegetation, such as cabbage palm, at the lower strata, it has not been effective at removing larger plants. Recognizing that the restoration will not result in a return to historical conditions should be viewed as an opportunity, not as a hindrance. Acknowledging this can, for example, lead to identification of more realistic management targets and metrics that are dynamic and better connected to adaptive management.

TABLE 3-3 Examples of Issues That Have Reduced the Effectiveness of the Monitoring Program at Picayune Strand

Issue	**Examples**
Sampling protocols and investigator training vary	Macroinvertebrate sampling intensity and identification has varied with researcher
Sampling methods are biased towards some species	Beder fish traps attract the invasive African jewelfish; Auran sampling method is biased toward one species
Increased hydroperiod reduces ability to access sites	Some vegetation sampling sites are not accessible under high water conditions, resulting in data gaps
Drought and dry periods	Fish sampling sites were often dry, leading to reduced sample size
Fire control	Fire control and suppression can increase soil temperature; equipment can cause erosion and destroy transect vegetation; fire has destroyed some sampling devices
Unclear definition of success	Degree of similarity between control and restored that would be considered successfully restored is not defined
Inadequate sample size	Low power for tests comparing vegetation control and restored sites

Adaptive management offers an opportunity to revisit goals, based on new information and analyses of monitoring data, to refine the project goals and objectives. For example, a shift in focus from eliminating cabbage palm to inhibiting its growth might be more realistic and make better use of limited resources. Rather than striving to replicate the plant and animal abundance from the predrainage system in Picayune Strand under a changing climate, a more realistic goal might be to increase the abundance of desirable flora and fauna and improve the resilience of the region to future change. Such a goal recognizes not only the habitat value of Picayune Strand but the benefits that the project provides within a larger ecosystem, including the mangrove transition areas of the Ten Thousand Islands, Fakahatchee Strand, and ultimately Big Cypress National Park. Achieving satisfactory results requires the use of hydrologic restoration combined with fire management and invasive species control as critical components of the CERP project strategy.

TABLE 3-4 Summary of the Conditions of Four Non-native Invasive Vegetation Species in 2019

Invasive	**Upper Lakes**	**Kissimmee**	**Lake Okeecho-bee**	**East Coast Region**	**West Coast Region**	**Everglades**	**Florida Bay & Southern Estuaries**	**Florida Keys**
Old World climbing fern	Y	R	Y	Y	R	R	G	G
Melaleuca	G	Y	G	Y	Y	Y	G	G
Brazilian Pepper	Y	Y	G	Y	R	R	Y	Y
Water Hyacinth	Y	Y	Y	Y	Y	G	G	G

NOTE: Red implies a severe negative condition; yellow, improving due to control measures; and green, under control.
SOURCE: Rodgers et al., 2020.

Melaleuca Eradication and Other Exotic Plants

The Melaleuca Eradication and Other Exotic Plants Project is a CERP effort to address the potential threat to restoration posed by non-native invasive plant species by mass rearing and releasing biological control agents. Five invasive species that are particularly problematic are the focus of major ongoing management efforts: Melaleuca (*Melaleuca quinquenervia*), Brazilian pepper (*Schinus terebinthifolia*), water hyacinth (*Eichhornia crassipes*), Old World climbing fern (*Lygodium microphyllum*), and air potato (*Dioscorea bulbifera*). The CERP biological control project addresses these species, centered at the U.S. Department of Agriculture's Invasive Plant Research Laboratory in Davie, Florida, where specific biological control agents—mostly insects—are developed and reared for release. CERP funding supported the 2013 completion of a mass rearing area at this facility, which expanded the production capacity for biological controls for several invasive nonindigenous plant species. More than 7.5 million biological agents have been reared and released through the program (A. Dray, U.S. Department of Agriculture [USDA], personal communication, 2020).

Melaleuca control involves prescribed burns, harvesting, chemical treatments, and biological controls. A recent study (Rayamajhi et al., 2018) indicates that the biological controls not only reduce the growth and health of melaleuca but also improve conditions for native plants by reducing leaf litter and seeds. Although biological treatments have the potential for negative effects (e.g., toxicity to insectivorous wildlife; Oelrichs et al., 1999), evidence indicates that these biological controls do not cause damage to other plants or wildlife (Center et al., 2008). Biological agents reared and released through the CERP-funded program include the melaleuca weevil (*Oxyops vitiosa*), the melaleuca psyllid (*Boreioglycaspis melaleucae*), the melaleuca midge (*Lophodiplosis trifida*), and the air potato beetle (*Lilioceris cheni*). These organisms are now well established on the landscape and no longer require additional releases. In many areas, biological and other controls have reduced the cover of melaleuca to the point where it is not considered a major problem. Melaleuca remains problematic in a few areas, such as Loxahatchee National Wildlife Refuge, where the melaleuca weevil cannot pupate in wet soils, and in the eastern Everglades Buffer, which has never been treated with biological agents. A fourth organism was awaiting approval for release in 2020 (M. Smith, USDA, personal communication, 2020).

With successful results from melaleuca biocontrol, the CERP mass rearing effort is now focused on biocontrol agents for Old World climbing fern, Brazilian pepper, and water hyacinth. The biological controls for these invasive plants, including the brown lygodium moth (*Neomusotima conspurcatalis*), lygodium gall mite (*Floracarus perrepae*), and waterhyacinth planthopper (*Megamelus scutellaris*), have been released in the greater Everglades. Information on the control of these four species is summarized in Table 3-4. Old World climbing fern is perhaps the most difficult to control, with dense infestations in the Kissimmee, Everglades, and west coast regions. Control through herbicide is common but only partially effective due to rapid reestablishment. The most abundant and widespread species is Brazilian pepper, which is currently managed through chemical and mechanical means. However, two biological control agents were approved for field releases in 2019. Mass rearing is under way and more than 65,000

Brazilian pepper thrips (*Pseudophilothrips ichini*) have been released. Releases of the second agent, a leaf galler (*Calophya latiforceps*), are expected in 2020.

Site 1 Impoundment

The Site 1 Impoundment Project (No. 3 on Figure 3-3) was originally envisioned to provide water storage (13,300 AF) and help alleviate demands on water in the Arthur R. Marshall Loxahatchee National Wildlife Refuge, thereby allowing for improved hydrologic conditions in the refuge (USACE, 2018a). In 2009, the project was divided into two phases. Construction of Phase 1, completed in 2016, was an $81 million effort that included modifications to the existing L-40 levee and construction of a 6-acre wildlife wetland area (USACE, 2018a; G. Landers, USACE, personal communication, 2016). Phase 1 is estimated to provide a 16 percent reduction in existing seepage at the L-40 levee (USACE, 2019b). Phase 2 of the project requires further congressional authorization necessitated by increased costs (USACE, 2018a). The SFWMD, however, in 2016 communicated to the USACE that it is no longer interested in constructing Phase 2, because of the high anticipated cost of the plan relative to the benefits provided (M. Morrison, SFWMD, personal communication, 2016). CERP planners have not formally deauthorized the project, but the project is not listed in the 2019 or 2020 IDS (USACE, 2019a, 2020c).

CEPP

CEPP is a multicomponent project (Figure 3-3, Nos. 10, 11, and 12) that was authorized in WRDA 2016 and modified with the addition of the EAA Reservoir, A-2 stormwater treatment area (STA), and canal conveyance improvements in WRDA 2018. WRDA 2020 clarified that CEPP includes the EAA Reservoir, with a combined authorized cost of $4.4 billion. With the authorized changes, CEPP components include a 240,000 acre-foot, 23-foot-deep reservoir, a 6,500-acre STA, and conveyance improvements. The project also improves the distribution of flow through seepage management, the filling of canals, and levee removal in the central Everglades. This large and complex project aims to reduce harmful estuary discharges and increase flows into the WCAs and Everglades National Park, while improving the timing and distribution of those flows (NASEM, 2018; SFWMD, 2018c; USACE, 2020a).

The project has been divided into three phases: CEPP North, CEPP South, and CEPP New Water. Construction of one early component of CEPP South (the S-333N spillway) began in September 2018 and was completed in October 2020. The S-333N spillway will increase the total capacity of the S-333 from 1,350 to 2,500 cubic feet per second (cfs), thereby helping to reduce high water levels in WCA-3A by moving higher flows to Everglades National Park during the wet season.[4] The CEPP South Project Partnership Agreement was executed in July 2020. The SFWMD has begun work for removing portions of the Old Tamiami Trail included in CEPP. The USACE has completed design work on gated culvert structures in the L-67A levee, spoil mound removal, and L-67 levee gaps features of CEPP South. Design work is proceeding for two other components of CEPP South: replacement of the S-356 pump station and the S-355W divide structure in the L-29 Canal associated with the Blue Shanty Flowway. Construction contracts for these features are scheduled for 2022 and 2023.

The SFWMD began construction of the inflow and outflow canal structures for the A-2 STA, a feature of CERP New Water, in April 2020. STA construction is expected to be completed by 2023. The committee commends the agencies on the fast implementation efforts under way in CEPP, which will help expedite restoration benefits to the heart of the Everglades.

Central and Western Everglades: Non-CERP Restoration Progress

Several major non-CERP projects are critical to the overall success of the restoration program and to the restoration of the central and western Everglades region. Progress in non-CERP projects that

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[4] See https://usace.contentdm.oclc.org/digital/api/collection/p16021coll7/id/7551/download.

contribute to improving water quality are discussed in this section. Chapter 4 describes the benefits expected from the Combined Operating Plan for the Modified Water Deliveries Project to Everglades National Park and the C-111 South Dade Projects, designed to restore flow to Northeast Shark River Slough.

Everglades Water Quality Treatment

Achieving water quality goals—specifically total phosphorus concentrations in the STA discharges south of Lake Okeechobee—is critical to progress in making additional water available to the remnant Everglades (see Chapter 2). Thus, progress addressing water quality throughout the watershed has implications for CERP progress. Additionally, water quality affects the capacity to reach CERP ecological objectives regarding habitat quality throughout the ecosystem. Trends and progress on major state water quality initiatives to address phosphorus are reviewed in this section.

As mandated under the Everglades Forever Act, the State of Florida is mitigating phosphorus inflows to the Everglades Protection Area largely through watershed best management practices and the construction and operation of large constructed wetlands, known as STAs. The STAs are located south of Lake Okeechobee and include five constructed wetland complexes (STA-1 East [STA-1E], STA-1 West [STA-1W], STA-2, STA-3/4, and STA-5/6; Figure 3-12). The design and operation of the STAs is focused on decreasing total phosphorus concentrations and loads of surface waters prior to discharge into the Everglades Protection Area (Chimney, 2020). In 2012, the U.S. Environmental Protection Agency (EPA) established a water quality–based effluent limit (WQBEL) for total phosphorus in STA discharge to “not exceed: 13 µg/L as an annual flow-weighted mean in more than 3 out of 5 water years on a rolling basis; and 19 µg/L as an annual flow-weighted mean in any water year” (Mitchell and Mancusi-Ungaro,

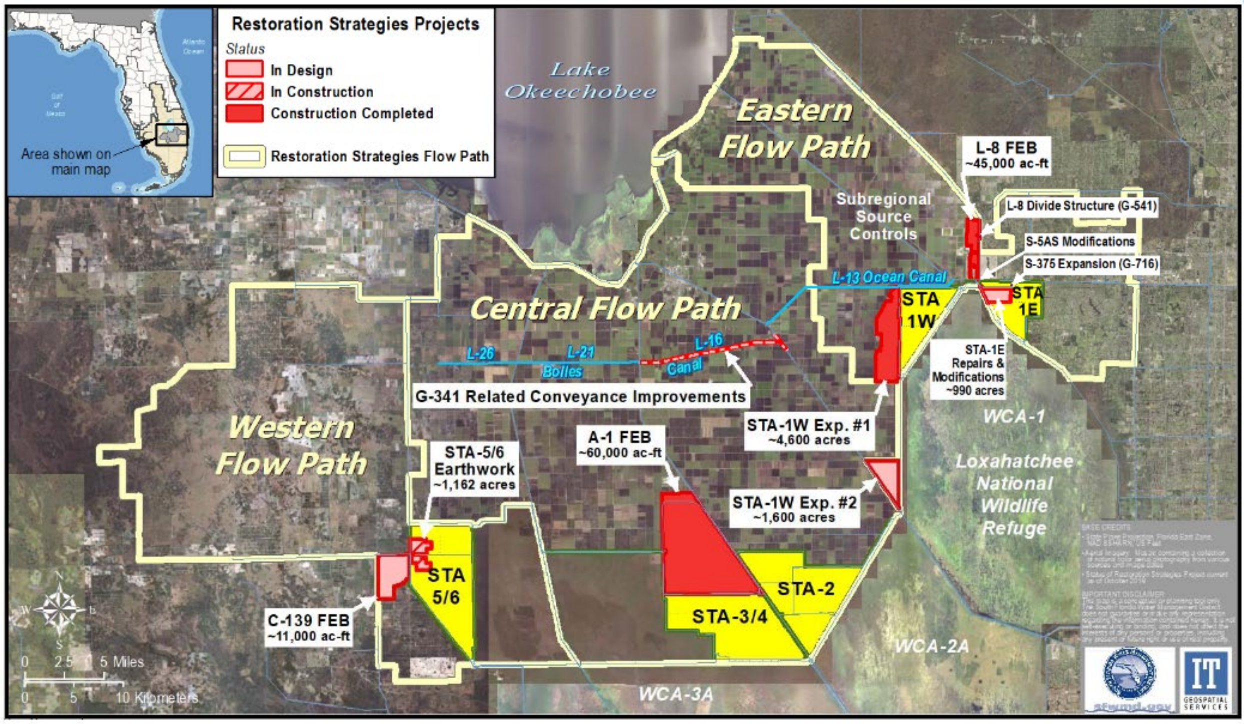

FIGURE 3-12 Location of the Everglades stormwater treatment areas (STAs) in yellow: STA-1E, STA-1W, STA-2, STA-3/4, and STA-5/6 and the locations of Restoration Strategies projects, including additional STAs, STA earthwork, and flow equalization basins (FEBs). SOURCE: Jacoby, 2020.

2012). This effluent limitation is intended to allow drainage to meet the 10 µg/L (or parts per billion) phosphorus criteria in the Everglades Protection Area. In 2012, the SFWMD developed its Restoration Strategies plan, which provides for expanding existing STA acreage and additional infrastructure improvements to meet the WQBEL. The Science Plan for Everglades Stormwater Treatment Areas (SFWMD, 2018b) was revised in 2018 to reevaluate and revise priorities based on understanding obtained during the 5 years of implementation. Restoration Strategies is expected to be fully constructed and operational by 2025, after which EPA will begin the process to assess compliance. Progress on Restoration Strategies project implementation is described in Table 3-5.

TABLE 3-5 Summary Status of Major Restoration Strategies Project

Component	Purpose	Status	Construction Completion
Eastern Flowpath			
L-8 FEB	Attenuate flow into STA-1E and -1W	Completed	2017
L-8 Divide Structures (G-716, G-541)	Assist movement of inflows and outflows to L-8 FEB	Completed	2016
STA-1W expansion (Phase 1)	Increase STA-1W effective treatment area	Undergoing initial flooding and optimization	2018
STA-1W expansion (Phase 2)	Increase STA-1W effective treatment area	Design completed in July 2020	Expected in 2022
G-341 Related Improvements	Divert flows (600 cfs max) to the west	Under construction	Expected in 2024
Central Flowpath			
A-1 FEB	Attenuate flow into STA-2 and -3/4	Operational testing completed in 2018.	2015
Western Flowpath			
STA 5/6 Earthwork	Improve the performance of STA-5/6	Undergoing initial flooding and optimization	May 2020
C-139 FEB	Attenuate flow into STA- 5/6	Design under way	Expected in 2023

SOURCE: https://www.sfwmd.gov/documents-by-tag/resstrategies; Jacoby, 2020, N. Hooseinny-Nabibaksh, SFWMD, personal communication, 2020.

Despite year-to-year variability associated with the quantity of water and loads of phosphorus treated, the extent of total phosphorus removal in the STAs has generally improved, with percent removal of inflowing total phosphorus peaking at 86 percent in 2016. In WY 2019, the flow-weighted mean outflow concentration of total phosphorus was 23 µg/L. The phosphorus removal performance varies across the STAs with effluent flow weighted mean concentrations of total phosphorus ranging from 12 µg/L for STA-3/4 to 55 µg/L for STA-5/6 for water year (WY) 2019 (Chimney, 2020). However, a time series of flow-weighted mean annual concentrations of total phosphorus over the most recent 10-year period does not show any consistent pattern of improvement (Figure 3-13). Overall, the total phosphorus removal effectiveness has been good, but effluent concentrations in most STAs remain far from the water quality targets. Only one STA (3/4) performs consistently well with flow-weighted annual concentrations that approach or meet the WQBEL, with minimal year-to-year variation. STA-2 has the next-best performance, with one year that met the WQBEL and several others that approached it, but with poor performance in the most recent years (2018 and 2019). An important factor contributing to the good performance of STA-3/4 is that it receives consistently low inflow total phosphorus concentrations. The inflow total phosphorus concentration in STA-3/4 in the most recent water year (2019) was 80 µg/L, compared to the average of 125 µg/L across all STAs (Chimney, 2020). However, mechanistic explanations for performance differences between STAs are still lacking, although developing a fuller understanding of why treatment performance varies among the STAs is one of the objectives of the

Science Plan that is currently in implementation (SFWMD, 2018b). Despite recent elevated phosphorus concentrations in several STAs, interior sites of the Everglades Protection Area remain in compliance with the total phosphorus criterion (Julian et al., 2020).

Completion and operation of additional STA expansion areas, flow equalization basins, and other improvements planned under Restoration Strategies are intended to improve the performance of STAs-1E, 1W, and 5/6. Both STA-2 and STA-3/4 are currently benefiting from the operation of the A-1 FEB, completed under Restoration Strategies in 2015, but STA-2 effluent remains well above the target, with an average flow weighted mean concentration of 26 µg/L over the past 5 years (C. Armstrong, SFWMD, personal communication, 2021). High flows in 2018 contributed to poor STA performance that year. The period of record for the operation of the A-1 FEB is short and may not be long enough to judge its effectiveness. The 2018 STA Science Plan (SFWMD, 2018b) indicates that the A-1 FEB has reduced peak flows and improved overall performance of the STAs. The 2018 Science Plan also suggests that a number of other factors should be examined to improve STA performance, including operational and design refinements, enhanced vegetation based treatment, and reduced internal loading of phosphorus. As the period of record for the A-1 FEB is extended and the other STA enhancements come online, a quantitative analysis of the factors influencing STA removal efficiencies, as suggested in the 2018 Science Plan, would be critical to help guide future STA improvements toward meeting the WQBEL and redistributing flows in CEPP.

An important further consideration is the longer-term performance of the STAs. With long-term loading with phosphorus-enriched influents, there is a likelihood that soils within the STAs will become saturated with respect to phosphorus inputs, reducing the effectiveness of treatment. Long-term model simulation suggests that, over the course of STA operation, the quantity of total phosphorus in soil will

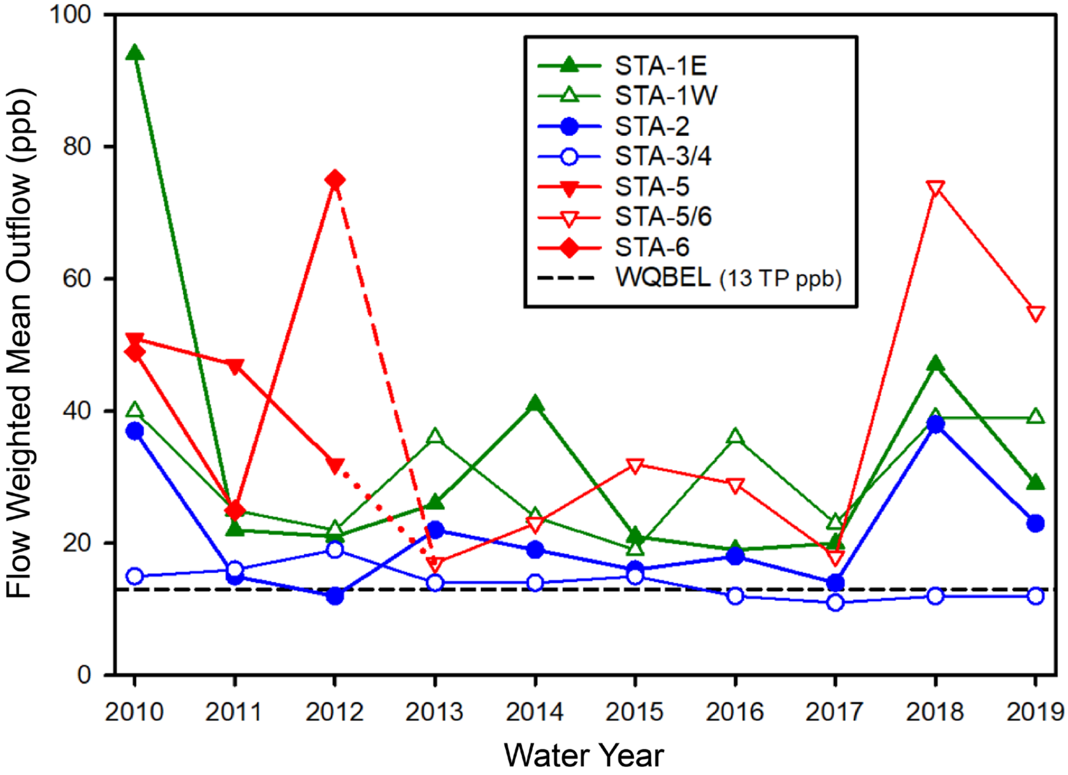

FIGURE 3-13 Time series of flow-weighted mean annual concentrations of total phosphorus in effluent for individual STAs over 2010-2019. Note that earlier STAs 5 and 6 were monitored separately but were combined in 2013. The value of the WQBEL is shown for reference. SOURCE: Data from Chimney, 2014, 2015, 2017a, 2018, 2019, 2020; Germain and Pietro, 2011; Ivanoff et al., 2012, 2013; Pietro, 2016.

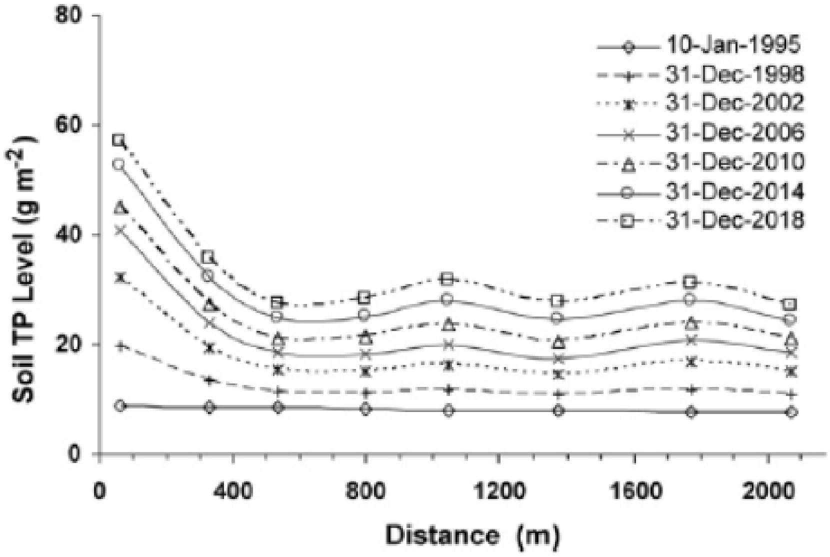

FIGURE 3-14 Model-predicted pools of total phosphorus (TP) for the upper 10 cm of soil in an STA at different times over a 24-year simulation period. For this scenario a total phosphorus loading of 2.41 g/m^2-yr was assumed. Distances reflect distance from the inflow. SOURCE: Paudel et al., 2010. Reprinted with permission; copyright 2010, ELSEVIER.

accumulate, with more pronounced increases in the cells of the STA adjacent to the inlet (Paudel et al., 2010; Figure 3-14). Paudel et al. (2010) compared model-simulated sediment accumulation of total phosphorus against measured values, finding good agreement. This or a similar STA model could be used to analyze recent observations, including spatial accumulation patterns in sediments, to gain insight into the long-term function of STAs for nutrient accumulation and removal.

Recent observations show that long-term nutrient loading to the STAs has resulted in accumulation of phosphorus-enriched materials in the upstream areas of the flow path of floc, emergent aquatic vegetation, and submerged aquatic vegetation (Reddy et al., 2020). This input has decreased nitrogen-to-phosphorus ratio (N:P) in floc and recently accreted soils within STAs, resulting in a shift from phosphorus limitation toward nitrogen limitation. Excess bioavailable phosphorus beyond the demand by microbes, algae, and plants will likely be exported from the STAs. Therefore, it is essential that STA management extend beyond total phosphorus to also include the stoichiometry of nutrient loading (including carbon and nitrogen). For example, FEBs could be operated to create high N:P in inflow nutrient loads to induce ecosystem utilization of internal surplus phosphorus (Reddy et al., 2020) or cells could be maintained periodically to remove accumulated phosphorus.

Central and Western Everglades: CERP Projects in Planning—Western Everglades

One project, the Western Everglades Restoration Project, is currently in planning in the central and western Everglades region. The western Everglades extends westward from WCA-3A and the Everglades Agricultural Area and encompasses Big Cypress National Preserve, as well as reservations of the Seminole Tribe of Florida and the Miccosukee Tribe of Indians of Florida (Figure 3-3, No. 15). This area suffers from water quality impairment, particularly from phosphorus-laden runoff from agriculture landscapes in the north, and altered hydrology. Elevated nutrient levels have spurred changes in flora and fauna, degrading the biodiversity of the region and affecting habitats used for traditional cultural practices. Unnaturally high water stages drown tree islands along the perimeter of WCA-3A, while unnaturally dry conditions promote wildfires elsewhere within the western Everglades. The Western Everglades Restoration Project (WERP) is intended to reestablish ecological connectivity, restore hydroperiods and predrainage distributions of sheetflow, restore low-nutrient conditions to reestablish native vegetation, and promote ecosystem resilience. At 1,200 square miles, the WERP footprint is large, covering an area equivalent to the CEPP.

The WERP planning process was launched in August 2016 and, over the next 18 months, the WERP Project Delivery Team narrowed an initial array of alternatives to three alternatives and, from these, formulated a hybrid alternative, referred to as Alternative H (Figure 3-15). Alternative H included STAs and buffer zones to address water quality concerns, as well as conveyance features intended to direct water to historic sloughs. It also involved various flood protection features and degradation and backfilling of levees and canals that were constructed as a part of the C&SF Project. The preliminary cost estimate for Alternative H was estimated at $1.2 billion (Summa, 2019).

In July 2019, further work on WERP planning was suspended for a number of issues, the most contentious of which involved potential impacts on private properties in the project footprint. A

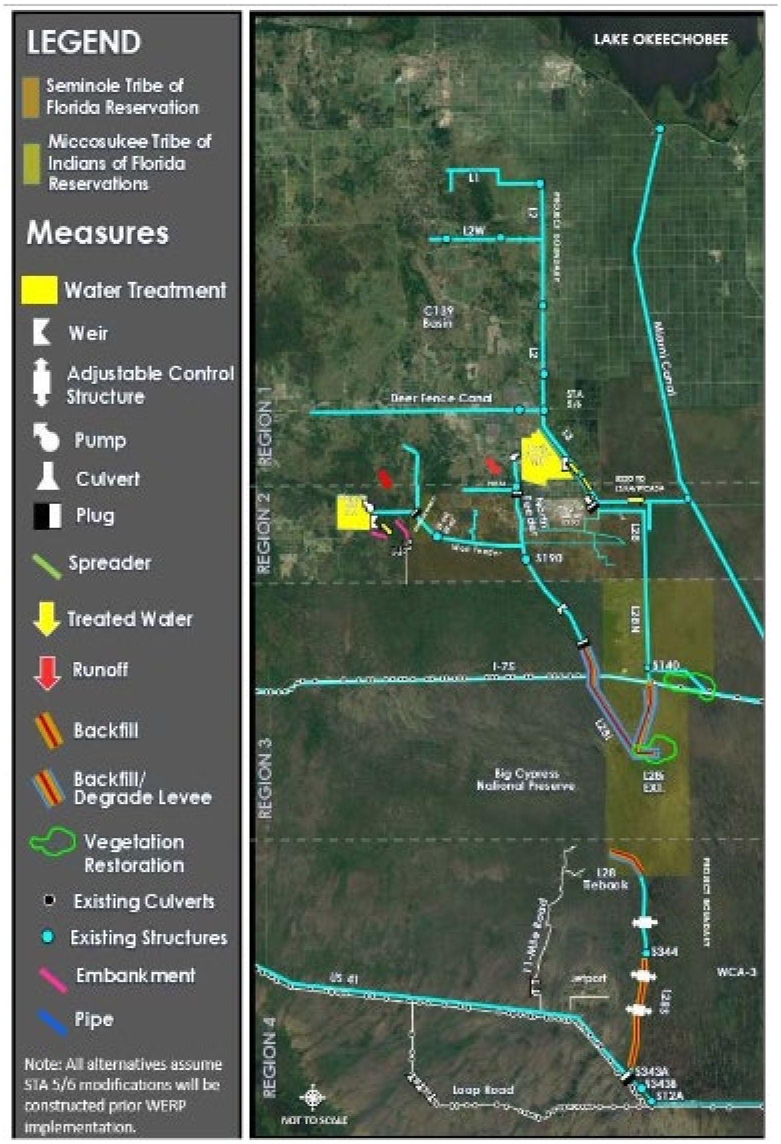

FIGURE 3-15 The features of WERP Alternative H, including stormwater treatment areas, backfilling canals and levees, and vegetation restoration. SOURCE: Gonzales, 2020.

preliminary analysis on 52 private holdings within the Big Cypress National Preserve within the WERP footprint suggested that all 52 parcels may be impacted by increased ponding and hydroperiods in a future with the WERP features in place, and land owners expressed concerns about possible land acquisitions. The Tribes also expressed concerns with components of the plan, including impacts to their land ownership rights, water quality, and project cost. After the USACE announced its intention to terminate the project planning process in October 2019, the SFWMD, Florida Department of Environmental Protection, Department of the Interior, Seminole Tribe of Florida, and Miccosukee Tribe of Indians of Florida worked collaboratively and pledged support for continuation of the planning process. As of January 2021, the planning process has restarted but is awaiting a waiver associated with planning time and budget. CERP agencies aim to complete the project implementation report and submit the Chief's report to Congress for authorization in 2022.[5]

CERP Projects Affecting the Northern Estuaries

Two CERP projects are under construction that directly affect the northern estuaries: the C-43 Reservoir and Indian River Lagoon-South. The impacts of these projects on the condition of the northern estuaries are discussed in more detail in Chapter 5.

C-43 Storage Reservoir

A major environmental issue in the estuary of the Caloosahatchee River on the west coast of Florida is the restoration and maintenance of appropriate salinity levels for aquatic organisms, particularly shellfish. Early in the 20th century, the course of the Caloosahatchee River was deepened and straightened, and canals were excavated in the river basin to drain agricultural lands and urban areas. As a result, during prolonged dry periods, freshwater flow to the estuary is greatly reduced, to the extent that saline water can migrate far up the river and kill beds of freshwater submerged plants. During periods of heavy rainfall, large volumes of nutrient- and sediment-rich freshwater are transported into the estuary, affecting habitat quality for seagrasses, oysters, and other aquatic organisms (see also Chapter 5). The Caloosahatchee River (C-43) West Basin Storage Reservoir (Figure 3-3, No. 8) is a CERP project designed to impound up to 170,000 AF of stormwater runoff from the C-43 drainage basin or from Lake Okeechobee during wet periods (USACE, 2019d). The C-43 reservoir is predicted to reduce high-volume events (mean monthly flows of >2,800 cfs) by about 14 percent and very high flows (mean monthly flows of >4,500 cfs by 23 percent. The benefits during dry periods are even greater, when this stored water can be released to supplement low river flows to maintain optimal salinity levels in the estuary and is available for water supply. The project is expected to reduce low flow events (mean monthly flows of <450 cfs) by 77 percent (USACE and SFWMD, 2014). Construction is under way, with completion anticipated by 2023 (USACE, 2020c). As a result, it is too soon to see natural system benefits from this project.

The Florida Department of Environmental Protection and SFWMD are currently conducting a feasibility study to examine water quality treatment options for water leaving the C-43 reservoir. Water quality treatment is being considered because of the potential for the stored water containing elevated nutrient levels to support the growth of algae in the reservoir and seed harmful algal blooms in the Caloosahatchee Estuary. Because the feasibility of water quality treatment is being considered after the reservoir has been planned and partly constructed, options for effective treatment of algal blooms in general and toxic blooms in particular may be because most available land for an STA is upgradient of the reservoir discharge.

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[5] See https://evergladesrestoration.gov/content/wg/minutes/2021meetings/012821/6_USACE_SFER_Overview.pdf.

Indian River Lagoon-South

The Indian River Lagoon and St. Lucie Estuary are biologically diverse estuaries located on the east side of the Florida Peninsula, where ecosystems have been impacted by similar factors as those that have impacted the Caloosahatchee River estuary—surges of freshwater from Lake Okeechobee and canals in the watershed and polluted runoff from farmlands and urban areas (USACE and SFWMD, 2004b). The Indian River Lagoon-South Project (Figure 3-3, No. 4) is designed to reverse this damage through improved water management, including the 50,600-AF C-44 storage reservoir, three additional reservoirs (C-23, C-24, and C-25) with a total of 97,000 AF of storage, three new STAs, dredging of the St. Lucie River to remove 7.9 million cubic yards of muck, and restoring 53,000 acres of wetlands. The project also involves the restoration of nearly 900 acres of oyster habitats and 90 acres of artificial habitat for submerged aquatic vegetation. Construction is under way on the C-44 reservoir and one of the three STAs, with estimated completion in 2021 (USACE, 2020d). Because no project features have been completed, there is no natural system restoration progress to report.

Loxahatchee River Watershed Restoration

The Loxahatchee River watershed once connected the sawgrass and ridge and slough habitats of the Everglades to the coast. The natural mouth of the river sometimes closed after storms due to blockage by shoaling of sand. The river system has been altered substantially over the past century. Jetties were placed on the inlet in the 1920s, and a deep channel was dredged through the inlet in the 1940s. In the 1950s, as part of the Central and Southern Florida project, several features (C-18 Canal, C-18W Canal, and the S-46 structure) cut off the northwest fork of the Loxahatchee River from Loxahatchee Slough and the rest of the watershed, reducing inflows. The Southwest Fork was channelized and flows increased through canal drainage. The connection of the river to the watershed was also altered by urban and agricultural development and wetland degradation which limited the storage of excess waters, resulting in periods of either excessive or limited flows to the Loxahatchee River estuary. The resulting changes in natural land cover, including up-river migration of mangrove and the displacement of cypress, raised concern, especially in the area designated as a Wild and Scenic River (FDEP, 2010).

The Loxahatchee River Watershed Restoration Project (Figure 3-3, No. 13), authorized in WRDA 2020, seeks to capture, store, and redistribute freshwater currently lost to tide, rehydrate natural areas in the headwaters, reduce peak discharges to the estuary, and improve the resilience of estuarine habitats by altering the timing and distribution of water from upstream. Planned components of the project (Figure 3-16) include wetland restoration and hydrologic improvements within the watershed, a single 9,500-AF reservoir, four aquifer storage and recovery (ASR) wells, and several structures related to connectivity in the southern part of the watershed. RECOVER recommended that the project include ecotoxicological testing related to ASR, consistent with the findings of NRC (2015). The project leverages extensive publicly owned land within the watershed, allowing improvements to hydrology to occur despite a heavily urbanized portion of the system. The total first cost of the project is $741 million (USACE and SFWMD, 2020a), and well over a quarter of the cost is associated with the C-18W reservoir.

Together the components of the project are expected to deliver 98 percent of the wet season restoration flow target and 91 percent of the dry season restoration flow target in the Northwest Fork of the Loxahatchee River (USACE and SFWMD, 2020a). These flows are expected to limit saltwater penetration in the estuary, conserve the remaining cypress, and promote the recovery of freshwater vegetation (e.g., *Vallisneria*) and other habitats important for estuarine species such as manatee and oysters. The project benefits were examined relative to three sea-level rise scenarios estimated based the Miami Beach tide gauge according to USACE guidance. Curves were adjusted to a 2020 baseline resulting in the following changes by 2070 for the three scenarios: low, 0.39 feet; intermediate, 0.86 feet; and high, 2.36 feet. These rates are within the range identified in the 2019 update to the Unified Sea Level Rise Projection for Southeast Florida for most projects within a short-term planning horizon (up to 2070) (Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group, 2020). The analysis showed that there was

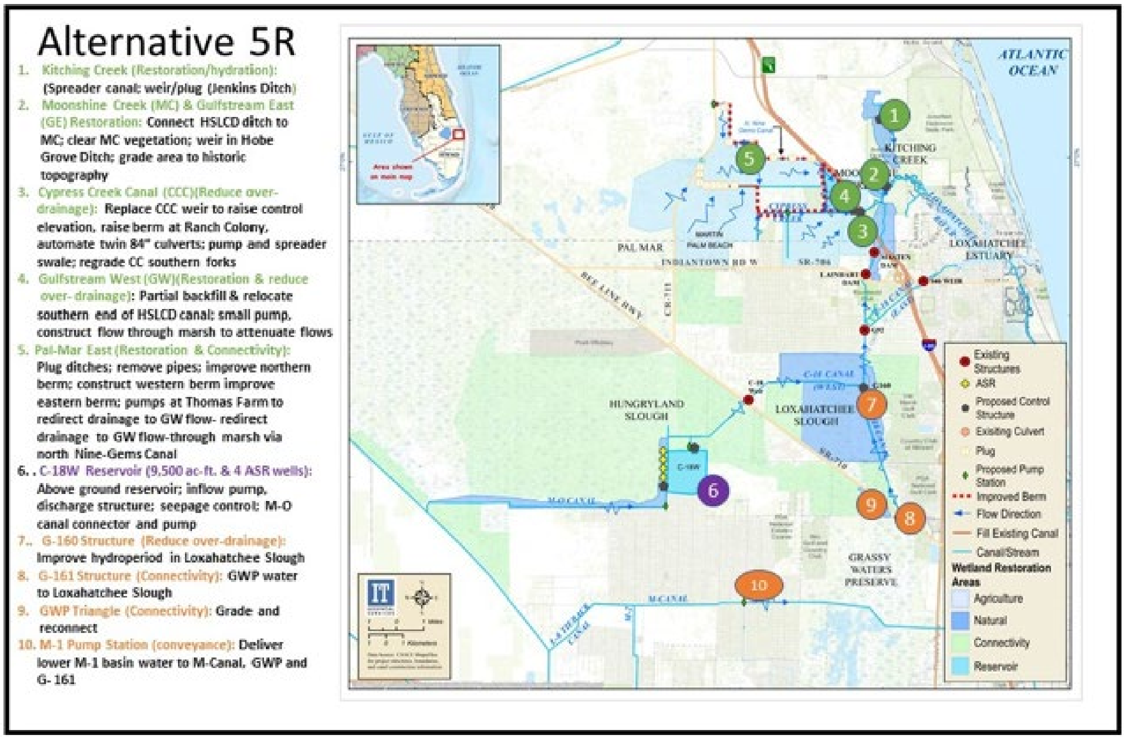

FIGURE 3-16 Components of the tentatively selected plan for the Loxahatchee River Watershed Restoration Project. SOURCE: USACE and SFWMD, 2020a.

little effect anticipated on project performance across the three sea-level rise scenarios. The benefits of the project are generally greater in the dry season. This use of hydrodynamic modeling of the Northwest Fork of the Loxahatchee River and the estuary to evaluate sea-level rise scenarios represents an important advance in analyses for project planning compared to prior CERP efforts.

Non-CERP Project Benefits to the Northern Estuaries and Lake Okeechobee

The CERP is just one of a broad array of state and federal programs intended to benefit the condition of Lake Okeechobee and the Northern Estuaries through improvements in water quality and quantity (Table 3-6). In terms of water quantity, the ongoing revision of the Lake Okeechobee System Operating Manual, a non-CERP effort, has the potential to substantially change these volumes and timing of lake discharges and affect the benefits that can be provided by CERP projects. Of the non-CERP programs affecting water quality, Florida's implementation of total maximum daily loads (TMDLs) and basin management action plans (BMAPs) through the Clean Water Act is particularly important to the estuaries of South Florida and Lake Okeechobee (Box 3-1). Progress in these efforts is discussed in this section.

Water Quantity: Lake Okeechobee System Operating Manual

In 1930, Congress authorized the Herbert Hoover Dike, which now encircles most of Lake Okeechobee with 143 miles of embankment, five inlets/outlets, nine navigation locks, and nine pump stations. The capacity of water to flow into the lake greatly exceeds the capacity to flow out, and after large rain events, runoff can result in a rapid increase in lake level. Water levels in the lake are regulated by the USACE based on a regulation schedule that is a set of seasonally varying rules guiding lake

TABLE 3-6 Partial List of Management Initiatives, Responsible Agency, and Intended Purpose Affecting the Northern Estuaries

Program or Initiative	**Responsible Agency**	**Intended Purpose, Related to Estuaries**
Central Everglades Restoration Plan	USACE and SFWMD	Improve the ecological and input flow conditions of the estuaries
Implement Clean Water Act in Florida, including National Pollutant Discharge Elimination System (NPDES) and Section 404 permits, water quality criteria, Section 303(d) listings and total maximum daily loads (TMDLs), basin management action plan (BMAP) to meet TMDLs, and non-point-source management	Florida Department of Environmental Protection (FDEP) and U.S. Environmental Protection Agency (EPA)	Protect water quality and designated uses of Florida surface waters, including estuaries, beaches, and coastal waters; impose limitations on point-source discharges to and non-point-source pollution of Florida's surface waters, including the estuaries and coastal waters out to 3 miles
Best management practices	FDEP and Florida Department of Agriculture and Consumer Services (FDACS), with impetus and funding from U.S. Department of Agriculture	Reduce agricultural loads of regulated pollutants, including the nutrients nitrogen (N) and phosphorus (P) in both organic and inorganic forms, pesticides, and sediment/turbidity, including to Florida estuaries
Lake Okeechobee System Operating Manual	U.S. Army Corps of Engineers (USACE)	Reexamine the opportunities to balance the authorized project purposes for flood control, water supply, navigation, recreation, and preservation of fish and wildlife resources
Northern Everglades and Estuaries Protection Program	South Florida Water Management District (SFWMD), FDEP, FDACS	Developed protection plans for the Caloosahatchee and St. Lucie river watersheds and coordinated state restoration efforts in these basins and in the Lake Okeechobee watershed
Dispersed Water Management	SFWMD	Provide water storage and nutrient removal north of Lake Okeechobee
Lake Okeechobee Watershed Construction Project	SFWMD	Improve quality to achieve the TMDL for Lake Okeechobee and thereby improve the quality of water discharged to the northern Everglades ecosystem
Minimum Flows and Minimum Water Levels	SFWMD and other regional Water Management Districts	Establish flows for rivers, streams, and estuaries and levels for lakes, wetlands, and aquifers below which further withdrawals would be significantly harmful to the water resources or ecology of the area
Climate Change Resilience Efforts	USACE, FDEP, SFWMD, counties, cities	Strengthen planning efforts for climate change adaptation and mitigation, which includes planning for sea-level rise and changes to coastal features
Coastal Zone Management Planning pursuant to the federal Coastal Zone Management Act	EPA, National Oceanic and Atmospheric Administration (NOAA), FDEP	Plan coastal development in order to protect key natural features while still allowing multiple uses along the coast, including energy development, recreation, and fisheries
National Estuary Program (NEP) in Florida--Coastal and Heartland National Estuary Partnership; Indian River Lagoon NEP; Sarasota NEP; Tampa Bay NEP	EPA, FDEP, local partners	Protect and restore estuaries of national significance

BOX 3-1 Protecting Water Quality under the Clean Water Act: TMDLs and BMAPs

The Clean Water Act, 33 U.S.C. §§1251-1388, is the nation's leading statute to protect water quality. While it is a federal statute, Congress always left certain parts of water quality law—e.g., water quality standards, non-point-source pollution control—to the states, and, in addition, Congress designed the Clean Water Act so that states could assume permitting authority. Like most states, Florida sought and received delegated authority from the U.S. Environmental Protection Agency (EPA) to administer the National Pollutant Discharge Elimination System (NPDES) permit program within state boundaries pursuant to §1342. The Clean Water Act applies to estuaries (33 C.F.R. §328.3(a)(1); 40 CFR §120.2), and because these waters are also considered part of the state, they require water quality standards (*id.* §1313(a)-(c)). Florida's regulatory programs under the Clean Water Act address point sources of pollution, such as wastewater treatment plants and industrial discharges (33 U.S.C. §1362(14)), and nonpoint sources such as agricultural and urban runoff (33 U.S.C. §1329) to ensure that all surface waters in Florida meet the water quality standards established by the Florida Department of Environmental Protection (FDEP). If a waterway in Florida does not meet its water quality standards, then the state is supposed to establish a total maximum daily load (TMDL) for that waterbody. A TMDL quantifies the total amount of the problematic pollutants (e.g., nutrients, sediment, specific toxics) that the waterway can retain and still meet its water quality standards and serves as a planning mechanism for restoring water quality. The TMDL sets pollutant allocations for point sources like municipal and industrial wastewater through the NPDES while non-point-source reduction actions are implemented via a number of programs at the federal, state, and local levels. In Florida, Basin Management Action Plans (BMAPs) are developed with stakeholders to establish a comprehensive set of point- and non-point-source strategies to achieve the pollutant reductions established by the TMDL, including NPDES limits on wastewater facilities, urban and agricultural runoff best management practices, and conservation programs. The water quality–limited waterbodies, TMDLs and TMDLs in progress, and BMAPs implemented and in progress in southern Florida are shown in Figure 3-17.

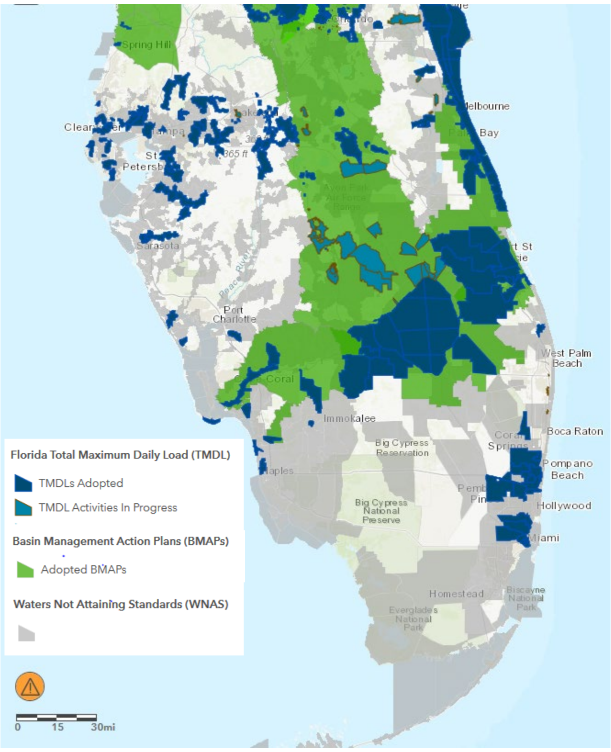

FIGURE 3-17 Florida's implementation of the Clean Water Act in southern Florida. The watershed-specific TMDLs typically address fecal coliform, nutrients, or both, although some address dissolved oxygen. Additionally, there is a statewide TMDL for mercury. SOURCE: https://floridadep.gov/dear/water-quality-restoration/content/impaired-waters-tmdls-and-basin-management-action-plans; https://floridadep.gov/dear/water-quality-evaluation-tmdl/content/final-tmdl-reports.

operations. If lake level exceeds an upper boundary set by the regulation schedule, water must be released to reduce the risk of failure of the Herbert Hoover Dike. Lake level is allowed to rise prior to the winter dry season to ensure that the amount of water is adequate to supply downstream agricultural irrigation and urban uses in South Florida. The lake level is lowered before the summer wet season to provide for maximal storage capacity to accommodate heavy rain events and tropical storms that may occur. Extreme rain events, however, can quickly push the lake level above what is considered safe at a particular time of the year. Failure of the embankment would cause massive damage and loss of life. In 2004, the USACE classified the Herbert Hoover Dike as Level 1 (i.e., highest risk) with regard to safety, and a major rehabilitation project has been under way since 2007 to improve its condition. The project is expected to be completed by 2022, with an estimated cost of more than $1.8 billion in total (USACE, 2019c).[6]

The Lake Okeechobee System Operating Manual (LOSOM), authorized under Section 1106 of WRDA 2018, is an effort by the U.S. Army Corps of Engineers to reevaluate and establish an operations regime for management of Lake Okeechobee and is intended to coincide with the Hebert Hoover Dike rehabilitation in 2022. The overall aim of the project is to incorporate flexibility in Lake Okeechobee operations in a way that balances the congressionally authorized project purposes of flood control, water supply, navigation, recreation, and preservation of wildlife. More specifically, objectives include enhancing ecological conditions for the lake, estuaries, and the South Florida system, improving water supply, continuing to meet authorized purposes for navigation, recreation, and flood control, and managing risk to public health, safety, and property (T. Gysan, USACE, personal communication, 2020). The USACE will evaluate the alternatives through 2021.

The upcoming Lake Okeechobee Regulation Schedule revision (anticipated in December 2022) will provide an opportunity to evaluate the feasibility and the benefits and risks of allowing higher or lower water levels in the lake once the Herbert Hoover Dike repairs are complete to recapture some water storage, potentially benefiting the northern estuaries and the remnant Everglades ecosystem. Recent reports (Graham et al., 2015; NASEM, 2016) have emphasized the importance of water storage to meet the original Everglades restoration goals and to adapt to possible future changes in precipitation.

Water Quality

Given the importance of water quality to meeting CERP's objectives for the estuaries (see Chapter 5), recent patterns in water quality in Lake Okeechobee and the northern estuaries are discussed.

Lake Okeechobee water quality. The nutrient of greatest water quality concern within Lake Okeechobee historically has been phosphorus, although the lake is also an important source of water and nutrients to the northern estuaries (see Chapter 5). The TMDL for total phosphorus of 140 metric tons/year was established in 2001 (FDEP, 2001). Over the most recent 5-year interval (WY 2015-2019) the average annual load of total phosphorus to the lake was 600 t (Zhang et al, 2020), far exceeding the TMDL. Phosphorus loads are highly variable from year to year, with no clear trend over time, despite programs implemented in the watershed to reduce phosphorus runoff from agricultural land parcels and small basins. This pattern is attributed to legacy phosphorus from past sources that has accumulated in soils and sediments (Reddy et al., 2011).

The TMDL was established to achieve a concentration of total phosphorus below 40 μg/L to improve the structure and function of the lake ecosystem. Annual concentrations of total phosphorus in Lake Okeechobee have increased from the earliest measurements in the 1970s in a general upward trend continuing through WY 2019, with notable peaks associated with hurricane activity (see Figure 3-18). Recent (WY 2019) concentrations were nearly four times greater than the TMDL target of 40 μg/L. Over the long term, total phosphorus concentrations have greatly increased in the lake due to the high concentrations in inflowing waters coupled with a decline in the phosphorus retention capacity of lake sediments (Havens et al., 2009; Zhang et al., 2020). These increasing concentrations in Lake Okeechobee have adverse impacts on the northern estuaries, which receive periodic high-volume discharges when lake

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[6] See http://www.saj.usace.army.mil/Missions/Civil-Works/Lake-Okeechobee/Herbert-Hoover-Dike.

levels are elevated (see Chapter 5). The increasing concentrations have implications for the CERP and its plans to move more Lake Okeechobee water south into the remnant Everglades, because higher total phosphorus concentrations could challenge the capacity of STA infrastructure to meet the water quality discharge standards.

Evidence from prior studies in Lake Okeechobee (Aldridge et al., 1995; Phlips and Ihnat, 1995) together with new data from recent algal blooms (Kramer et al., 2018) indicate that cyanobacteria and algal blooms within Lake Okeechobee and the estuaries are promoted by both excessive phosphorus and nitrogen loading (Havens, 1995; Paerl et al., 2019). There have been long-term increases in total phosphorus concentrations in the lake related to sediment retention, coupled with slight decreases in total nitrogen concentrations, which may be driven by decreases in nitrogen inputs (Figures 3-18 and 3-19). However concentrations of both nutrients remain high. No TMDL has been set for nitrogen for Lake Okeechobee.

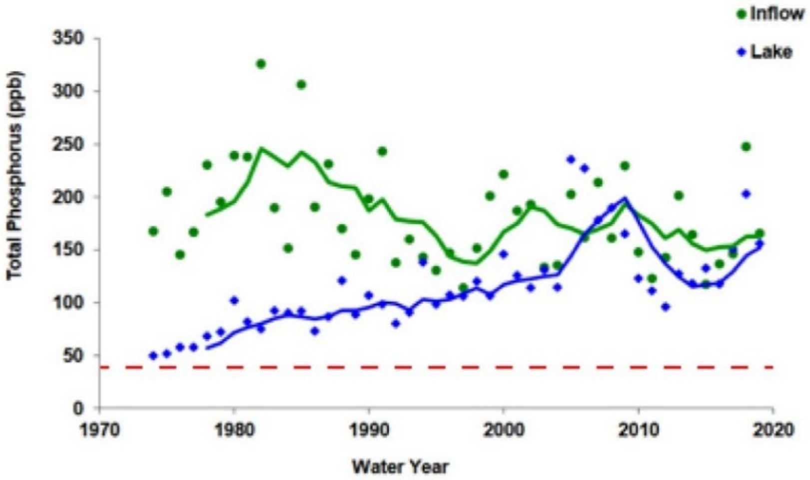


FIGURE 3-18 Total phosphorus concentrations in Lake Okeechobee and its inflows as annual averages and 5-year moving average trend lines. The target TMDL total phosphorus concentration is indicated (40 µg/L). SOURCE: Zhang et al., 2020.

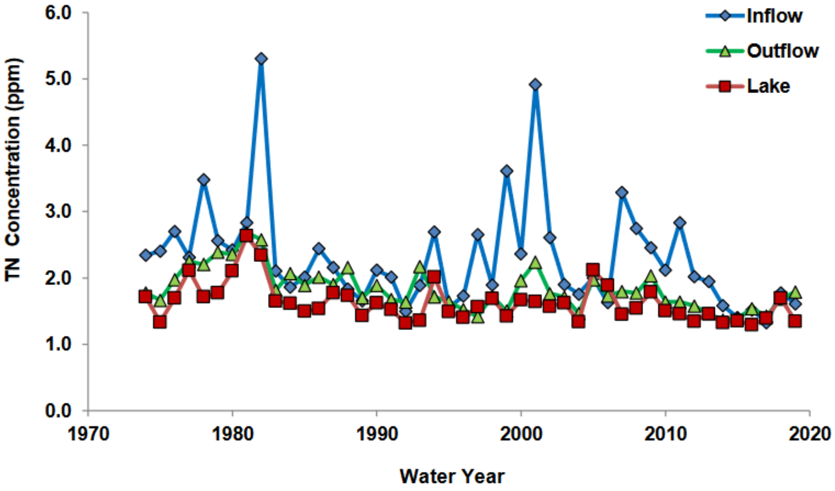


FIGURE 3-19 Average annual total nitrogen concentrations in Lake Okeechobee and its inflows and outflows. SOURCE: Zhang et al., 2020.

St. Lucie watershed nutrient loading. Annual total nitrogen and phosphorus loads to the St. Lucie Estuary vary greatly based on hydrologic conditions (Figure 3-20). FDEP (2008) set a TMDL for total nitrogen (summed from the individual contributing basins) of 544 metric tons/year to achieve an average daily nitrogen concentration of 0.72 mg/L in the St. Lucie Estuary. In 2006, this value represented a 47 percent reduction in the overall nitrogen loading across the basins. Recent more typical precipitation years have had total nitrogen loads nearly 2.5 times the TMDL, and in WY 2018, a high-flow year, the total nitrogen loading was nearly six times the TMDL (Figure 3-20b; Serna et al., 2020).

The TMDL for total phosphorus from all contributing basins was established at 61 metric tons/year to attain a target concentration of 81 µg/L phosphorus in the estuary. This TMDL was a 68 percent reduction in total phosphorus loading for the period of record at the time the TMDL was developed. Annual phosphorus loading in recent years has been at least three times the TMDL (Figure 3-20c).

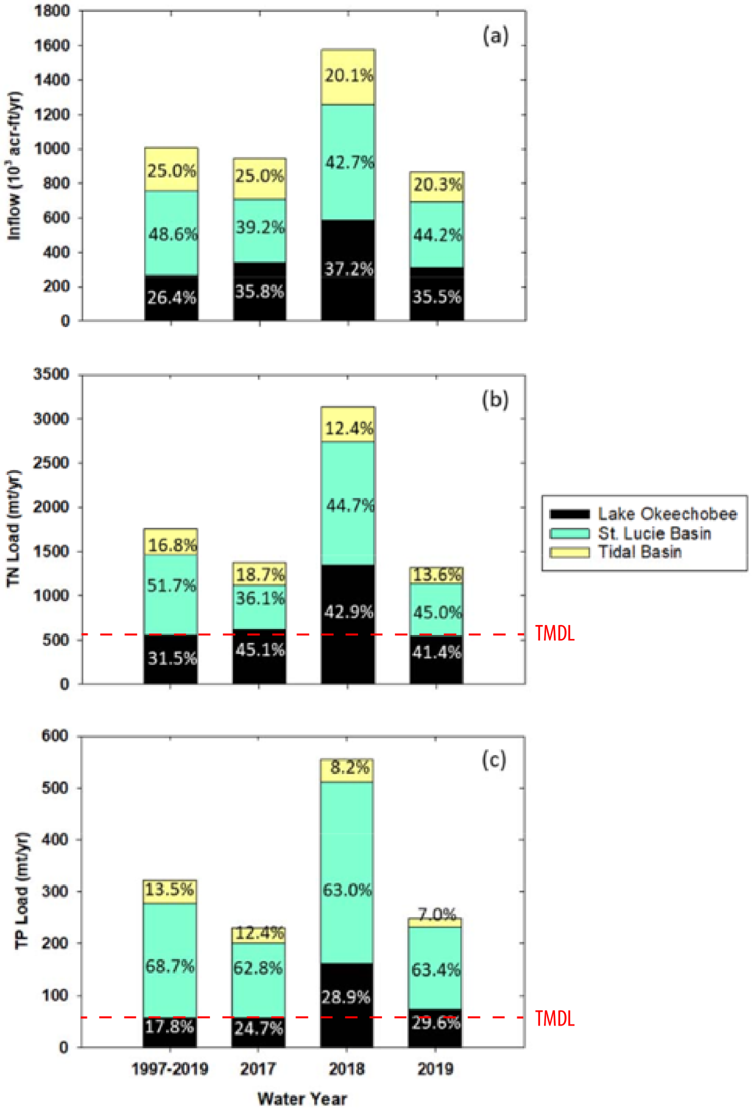


FIGURE 3-20 (a) Long-term and recent water inflows, (b) annual loadings of total nitrogen, and (c) annual loadings of total phosphorus from contributing areas to St. Lucie Estuary. For comparison, the level of the TMDL is indicated by the dashed red line. Note that these data as reported by the SFWMD are not the same as those FDEP uses to judge compliance with the TMDL. SOURCE: Serna et al., 2020.

Caloosahatchee River Estuary nutrient loading. FDEP (2009) established a TMDL of 4,120 metric tons of total nitrogen per year for the Caloosahatchee Estuary basin (FDEP Rule 62-304.800(2)), which required a 23 percent reduction in nitrogen loads to the estuary. The long-term average (1997-2019) for total nitrogen loading to the Caloosahatchee River Estuary was below the TMDL (Figure 3-21). However, during 2018 when algal blooms adversely impacted the local economy, the total nitrogen load was substantially higher at 5,300 metric tons/year (Figure 3-21b; Serna et al., 2020).

There is no TMDL for total phosphorus for the Caloosahatchee Estuary. In contrast to the St. Lucie Estuary, which showed variable phosphorus loads in recent years, in the Caloosahatchee Estuary, recent annual phosphorus loads have exceeded the long-term average (Figure 3-21).

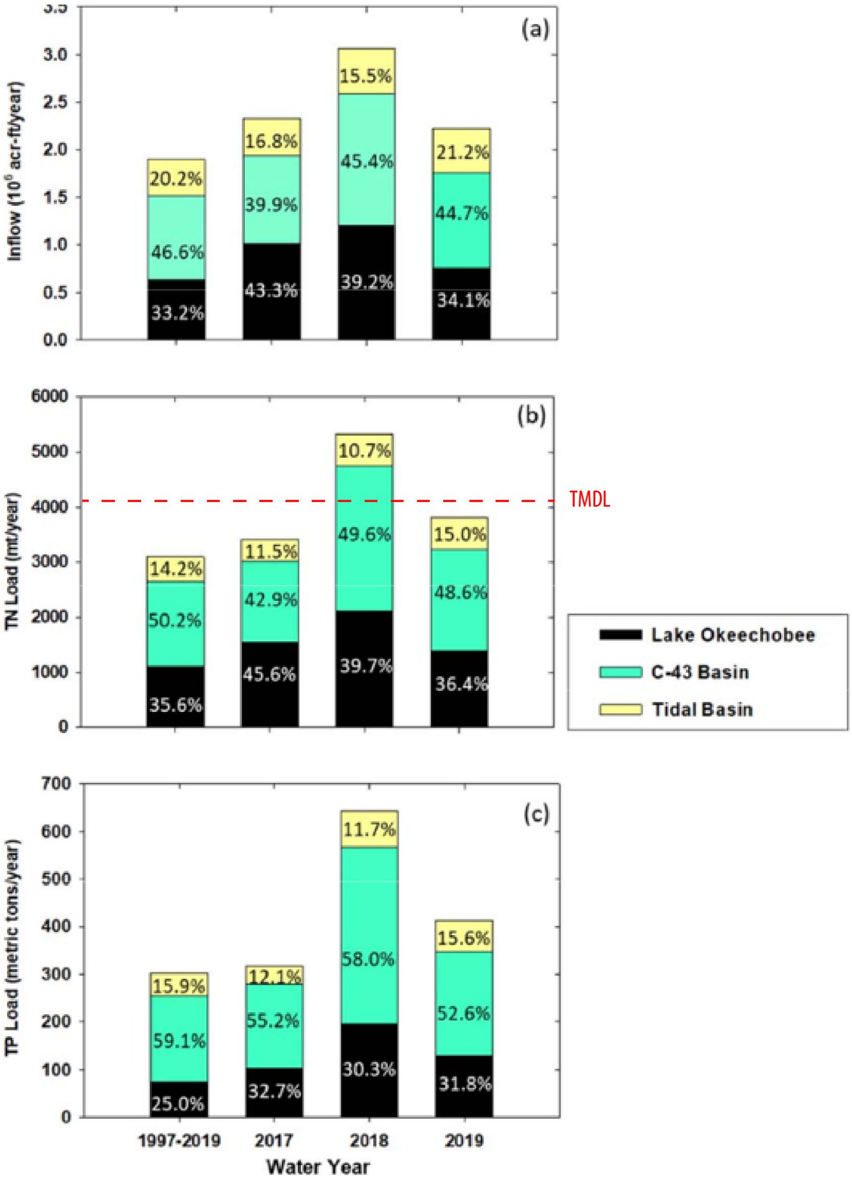


FIGURE 3-21 (a) Long-term and recent water inflows, (b) annual loadings of total nitrogen, and (c) annual loadings of total phosphorus from contributing areas to Caloosahatchee River Estuary. For comparison, the level of the TMDL is indicated by the dashed red line. Note that these data reported by the SFWMD are not the same as those FDEP uses to judge compliance with the TMDL. SOURCE: Modified from Serna et al., 2020.

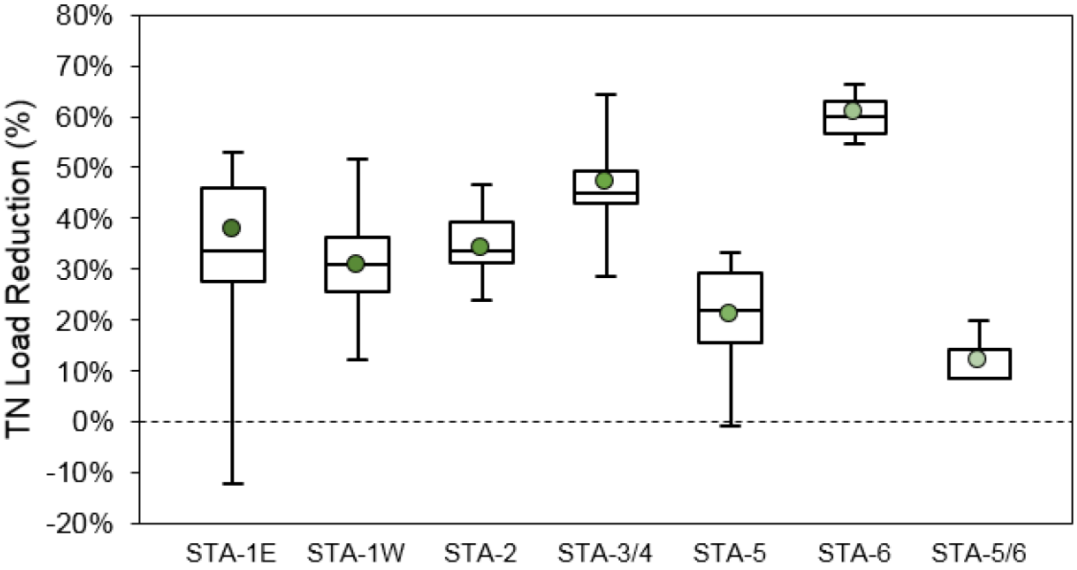


FIGURE 3-22 Box plot of percent reduction in annual total nitrogen loads in stormwater treatment areas. The percentage reduction in annual concentrations of total nitrogen for all STAs was correlated with inflow concentrations of total nitrogen (r = 0.71), while a much weaker linear relationship was evident between the influent load of total nitrogen (r = 0.26). NOTES: Box plot legend: horizontal line within box = median of data distribution (50th percentile); top of box = 75th percentile; bottom of box = 25th percentile; spreader bars = minimum and maximum removal values. Solid circles are average removal values over the period of record for each STA. Periods of record are 2007-2016 (STA-1E), 2004-2016 (STA-1W), 2003-2016 (STA-2), 2006-2016 (STA-3/4), 2004-2012 (STA-5), 2002-2007 (STA-6), and 2014-2016 (STA-5/6). In 2013 the flows from STA-5 and STA-6 were combined. SOURCE: Chimney, 2017b.

Nutrient management for the estuaries. Over the long term in both estuaries, significant fractions of the total loads of nitrogen and phosphorus are supplied both by the local watersheds and Lake Okeechobee (Figures 3-20 and 3-21). Thus, meeting estuarine water quality goals will require substantial nutrient reductions from local watersheds in addition to reduction of loading from Lake Okeechobee. Efforts are under way through BMAP to reduce nutrient loading (see Box 3-1).

The nitrogen loading challenges in the northern estuaries have increased interest in the capacity of STAs to treat nitrogen inflows (e.g.,Graham et al., 2020; Janicki Environmental, 2003). Chimney (2017b) found that the currently operating STAs, which are optimized for phosphorus removal, provide only modest reductions of influent total nitrogen. Over the period of record, the reduction in nitrogen loads for all STAs was 38 percent, with the extent of reduction ranging from 12 percent at STA-5/6 to 47 percent at STA-3/4 (Figure 3-22). A greater reduction in total nitrogen load was evident for STA-6 (61 percent), but this was attributed to large seepage losses between the inflow and outflow (Chimney, 2017b). STAs, in general, are most effective in removing dissolved inorganic fractions of nitrogen (ammonium, nitrate). The composition of total nitrogen in STA effluent, therefore, primarily comprises particulate nitrogen and dissolved organic nitrogen. Pisani et al. (2017) found that dissolved organic nitrogen dominated total nitrogen in the Caloosahatchee River. Moreover, they determined that only a mean of 15 percent of the dissolved organic nitrogen was biologically available, with the highest bioavailable fraction associated with drainage from Lake Okeechobee. The SFWMD is investigating approaches to remove dissolved organic nitrogen associated with the C-43 Reservoir (SFWMD, 2016a). This work includes bioassays to quantify the dissolved organic nitrogen in the estuary and mesocosms to assess nitrogen removal rates by different plants. The most successful treatments observed in the mesocosms will be scaled up in field cells. A more detailed understanding of removal of nitrogen species by STAs will be critical to inform decisions about the use of STAs in controlling nitrogen loads to coastal areas.

CERP Projects in Planning in the Northern Estuaries: Lake Okeechobee Watershed Restoration Project

One project with impacts for the northern estuaries is in the late stages of planning as of December 2020—the Lake Okeechobee Watershed Restoration Project (LOWRP). Located north of the lake, the Lake Okeechobee Watershed Restoration Project (Figure 3-3, No. 14) was designed to capture, store, and redistribute water entering the northern part of Lake Okeechobee to “improve lake stage levels, improve discharges to the Caloosahatchee and St. Lucie estuaries, restore/create wetland habitats, re-establish connections among natural areas that have become spatially and/or hydrologically fragmented, and increase available water supply” (USACE and SFWMD, 2019). A revised draft of the project implementation report was released in July 2019 (USACE and SFWMD, 2019), and a final project implementation report was released in August 2020 (USACE and SFWMD, 2020d). As of December 2020, the project had not been submitted to Congress for authorization.

The major project components in the final recommended plan include

- A shallow wetland attenuation feature with a storage volume of approximately 46,000 acre-feet;
- 80 ASR wells with a total storage volume of approximately 448,000 acre-feet per year; and
- Two wetland restoration sites, encompassing 4,800 acres (Figure 3-23).

The total first cost estimate (2020 price level) of the plan is $1.96 billion (USACE and SFWMD, 2020d).

FIGURE 3-23 Features of the Lake Okeechobee Watershed recommended plan. SOURCE: USACE and SFWMD, 2020d.

The Lake Okeechobee Watershed Restoration Project is expected to provide a smaller increment of additional storage north of Lake Okeechobee relative to that originally envisioned under the CERP (200 ASR wells and 250,000 acre-feet of surface storage) (USACE and SFWMD, 1999). Implementation of the project is expected to reduce total flows to the St. Lucie Estuary by 17 percent and to the Caloosahatchee Estuary by 36 percent (USACE and SFWMD, 2020d). By lowering the frequency, volume, and duration of freshwater released from Lake Okeechobee, LOWRP should reduce turbidity, sedimentation, nutrients, and salinity fluctuations that are detrimental to submerged aquatic vegetation, oyster communities, and fish habitat of the northern estuaries (see also Chapter 5). The project also increases the acreage of wetland habitat north of Lake Okeechobee.

The anticipated benefits of LOWRP to Lake Okeechobee ecology appear to be more modest. The percentage of time Lake Okeechobee is expected to be within the ecologically preferred stage envelope is 31.2 percent under the tentatively selected plan compared to 27.7 percent under the future-without-project scenario, which includes CEPP, Indian River Lagoon-South, and the C-43 Reservoir (USACE and SFWMD, 2020d).

The LOWRP planning process was unable to identify viable options for aboveground storage at depths envisioned by the CERP (>11.5 ft), so more than 90 percent of the storage in the LOWRP will be provided by 80 ASR wells completed within the Upper Floridan Aquifer and the deeper Avon Park Permeable Zone. Fifty-five ASR wells will be grouped in several clusters that are distributed along various tributaries of the Lake Okeechobee watershed, while the remaining 25 ASR wells will be grouped into three clusters that are co-located with the wetland attenuation feature. The purpose of combining ASR wells with the wetland attenuation feature is to enable more dynamic storage because ASR could be operated to recharge when the wetland attenuation feature is full. The benefits of the wetland attenuation feature without ASR or ASR wells with no aboveground storage feature were not presented. Whether the wetland attenuation feature, given its small size, could increase storage enough to meaningfully influence Lake Okeechobee water levels or discharges to the estuaries is unclear.

The planned LOWRP ASR system will be much larger than established Florida ASR systems, which have relied on fewer than 22 wells. Critical uncertainties remain with application of ASR at the large scale considered by the plan. The National Research Council (NRC, 2015) highlighted concerns regarding ecotoxicology that were not resolved in the ASR Regional Study (USACE and SFWMD, 2015) and suggested further field-scale research to address these questions. NRC (2015) also noted that disinfection permitting requirements were not uniformly achieved during the ASR pilot studies and recommended additional work to develop appropriate treatment strategies. Moreover, ASR recovery efficiencies exhibit considerable heterogeneity, and those areas within the LOWRP footprint with aquifer attributes suitable for supporting high recoveries have yet to be identified. These uncertainties can be effectively addressed by phased implementation of ASR using clusters of three to five wells. Consistent with the recommendations of NRC (2015), the final project implementation report proposes a phased approach to ASR construction. USACE and SFWMD (2020d) also proposes a schedule that delays construction of the wetland attenuation feature until the 55 watershed ASR wells are constructed, which is appropriate because the benefits of this aboveground storage feature are closely linked to performance of the co-located ASR wells.

Southern Estuaries

As discussed in more detail in Chapter 5, several CERP and non-CERP projects designed to improve the flow and distribution of water in the central Everglades also increase flows to the southern estuaries. Because the natural system benefits of the CEPP and the C-111 Spreader Canal projects to date are discussed earlier in this chapter, this information is not repeated here. This section focuses on the documented restoration benefits of the CERP Biscayne Bay Coastal Wetlands Project, with a brief discussion of non-CERP efforts and the recently launched Biscayne Bay and Southeastern Everglades Ecosystem Restoration planning effort.

CERP Projects: Biscayne Bay Coastal Wetlands (Phase 1)

The primary goal of the Biscayne Bay Coastal Wetlands (BBCW) Project is to reduce nearshore salinity and improve the ecological condition of wetlands, tidal creeks, and other habitats by increasing freshwater flows to Biscayne Bay and Biscayne National Park. As a consequence of historical hydrologic alteration and development, freshwater delivery to Biscayne Bay has been greatly reduced, particularly in the dry season, resulting in loss of wetlands and an increase in salinity along the western margin of the bay. The full BBCW Project, as outlined in the Yellow Book (USACE and SFWMD, 1999), envisioned restoration of wetland hydroperiods to 11,300 acres of the total 22,500 acres of wetlands through freshwater inputs; the project was not designed to reduce nutrient inputs. The footprint of Phase 1 of the BBCW Project is small; its goals are to restore about 400 acres of freshwater wetlands and increase water flows in another approximately 2,000 acres in three geographically distinct components: the Deering Estate Component, just north of the Biscayne Bay National Park, and the Cutler Wetlands and L-31E Flow-way Components, portions of which are within the national park (Figure 3-24; USACE and SFWMD, 2012).

FIGURE 3-24 Biscayne Bay Phase 1 coastal wetlands project locations. SOURCE: USACE and SFWMD, 2012.

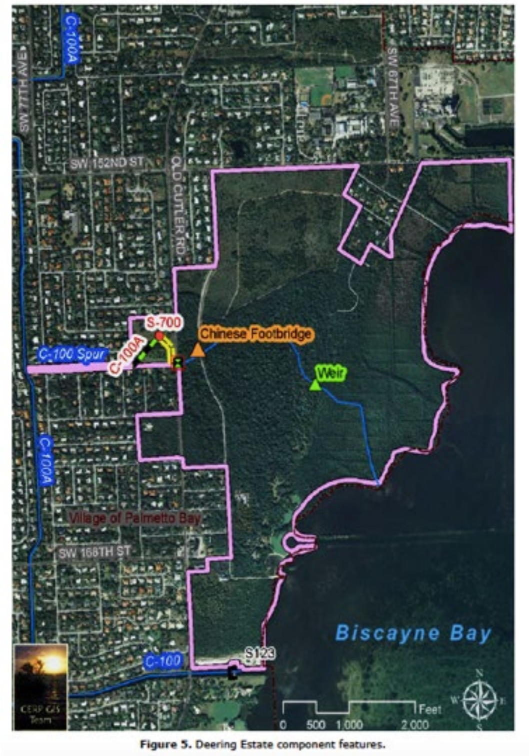


FIGURE 3-25 The Deering Estate footprint of the Biscayne Bay Coastal Wetlands Project. SOURCE: Charkhian, 2020.

Project implementation includes construction of pump stations, spreader canals, and culverts, and the reestablishment of flow-ways (USACE, 2019e). The Deering Estate Component was completed in 2012. In the past 2 years, the remainder of the 10 planned culverts in the L-31E Flow-way were also completed and were made operational in WY 2019. From August 2018 to mid-2020, the SFWMD operated a 40-cfs interim pump to increase water levels in the L-31E Canal to the optimal level of 2.2 feet National Geodetic Vertical Datum of 1929 (NGVD29) in order to increase water flow through the culverts to coastal wetlands east of the L-31E levee. The pump could operate only as long as there was excess freshwater to be diverted, which was often lacking. A critical challenge for each component, looking forward, is whether there will be an adequate supply of freshwater, especially during the dry season, to achieve established targets.

The USACE is expected to finish construction of the L-31E Component in 2024, which will include a total of five pump stations. Construction of the Cutler Wetlands Component is scheduled for 2021 (USACE, 2019e). Planning for Phase 2 of the BBCW has been incorporated into an integrated planning effort—the BBSEER (USACE and SFWMD, 2020b), which is beginning in summer 2020. The documented restoration benefits to date from the project components implemented are discussed below.

Deering Estate. The S-700 pump station on the C-100A spur canal within the Deering Estate is designed to restore historic freshwater flows through the Cutler Drain Slough and into the coastal wetlands, reducing nearshore salinity. The hydrologic goal was to redirect up to 100 cfs of water from the C-100A spur canal, that would otherwise flow through the S-123 structure, to the coastal wetlands (Figure 3-25), thereby reducing point-source freshwater discharges from S-123. To alleviate the hydrologic flashiness that occurred with intermittent pumping, the SFWMD moved to continuous pumping at a minimum rate of 25 cfs to maintain water flows to the coast. This change was slow to be implemented and was only initiated in WY 2019 (Charkhian, 2019; see also NASEM, 2018).

Monitoring results show clear improvement of hydrologic conditions in response to pumping. In WY 2019, which had greater than average rainfall, the S-700 pump station diverted 24,414 acre-feet of freshwater (up from 17,150 acre-feet in WY 2018) to the coastal wetlands (Charkhian, 2020) with 10,851 acre-feet discharged through S-123 at the southern edge of the estate (down from 40,686 acre-feet in WY 2018). These results demonstrate progress toward one project objective, which is to minimize discharge of water through the S-123 structure. When the S-700 pump station is operating, both ground- and surface-water salinity at wetland monitoring stations decrease markedly, to less than 1 practical salinity uni (PSU). Median salinity in Deering Estate Creek water decreased from 24.3 in WY 2014-2018 to 18.1 in WY 2019 (Charkhian, 2020). Vegetation within the vicinity of the Deering Estate component is responding to improved hydrology, as indicated by die-off of upland vegetation, the emergence of wetland species, and a modest expansion of sawgrass (*Cladium jamaicense*) (Charkhian, 2020).

FIGURE 3-26 The L-31E component of the Biscayne Bay Coastal Wetlands Project. SOURCE: Charkhian, 2020.

The L-31E Component. The goal of the L-31E Component is to improve habitat conditions by diverting water that would normally be released through the L-31E Canal to the adjacent coastal wetlands, thereby lowering nearshore salinities. A chronic challenge for the project is an insufficient supply of freshwater that limits flows from the canal through the L-31E culverts and into the wetlands (Figure 3-26). This condition has been in part due to the lack of pumps to move water into the canal and raise and maintain canal stage high enough (canal stage target level is 2.2 ft NGVD29) to promote outflow through the culverts. In WY 2019, the interim pump met the target canal stage in the wet season, but due to lack of water, canal stages were 1.9 ft NGVD29 in the WY 2018 dry season. The USACE began construction on the five L-31E pump stations, spreader swales, and recreation features in 2020.

The SFWMD has set a performance target to divert 4 percent of the total coastal discharges to the wetland as freshwater flow from the L-31E Canal, although this diversion is not specifically tied to ecological targets. Between water years 2012 and 2017, the project met the flow target in only 24 of the 84 months. In WY 2019, after the interim pump was installed, an average of 5.8 percent of water flow was diverted (5.3 percent of wet season flows and 6.3 percent of dry season flows). Pump operations have raised water levels in the canal, resulting in 35 weeks of inundation in the vicinity of the pumps. When the pump is running, salinity decreased to less than 5 PSU in the coastal wetlands 100 m downstream of the culverts (Charkhian, 2020), which meets the salinity target range of less than 20 PSU in tidal wetlands (USACE and SFWMD, 2012).

The ecological impact of the project is promising but remains limited by the availability of freshwater to move to the Bay. Sawgrass recruitment has been observed east and west of the L-31E Canal within the coastal wetlands and since 2013 the total cover of sawgrass increased by more than 9 acres east of the L-31E levee (Charkhian, 2020).

Non-CERP Projects

The non-CERP Combined Operational Plan, which establishes the operating rules for the C-111 South Dade and Modified Waters Deliveries to Everglades National Park projects, increases flows to eastern Florida Bay, and these benefits are discussed in detail in Chapter 4. Information on the collective benefits of planned restoration projects for the southern estuaries is also synthesized in Chapter 5. One additional non-CERP effort to evaluate the benefits of a seepage barrier on the eastern boundary of Everglades National Park is just beginning a public planning process, and is too early in its planning process to evaluate.

CERP Projects in Planning: Biscayne Bay and Southeastern Everglades Ecosystem Restoration

In September 2020, a 3-year planning process was launched for the large, multicomponent project BBSEER (USACE and SFWMD, 2020b). As with the CEPP, BBSEER is combining planning for multiple CERP components into an integrated planning process, including Biscayne Bay Coastal Wetlands (beyond Phase 1), C-111 Spreader Canal (Eastern Phase), South and West Miami Dade Reuse, and North Lake Belt. The committee did not review this effort, because it was launched late in the study process. Future needs for the southern estuaries are discussed in Chapter 5.

CONDITIONS AT A SYSTEMS SCALE

The RECOVER System Status Report (SSR) is compiled approximately every 5 years to present a systemwide update on the overall ecological condition of the Everglades ecosystem by synthesizing monitoring data as they relate to systemwide hypotheses and restoration goals, providing a description of the status and trends of system condition. The SSRs were envisioned as a key step in the CERP systemwide adaptive management process, by providing a measure of the extent to which the goals and objectives of the CERP are being met and identifying corrective actions for any major unanticipated findings (RECOVER, 2007b).

For the first time, the 2019 SSR (RECOVER, 2019) includes an Everglades Report Card; a stand-alone summary report of the status of the Everglades from 2012 to 2017 using ecosystem indicators and performance measures of the CERP. The Report Card uses clear and easy-to-understand graphics to describe the status of each of five reporting units including the entire Everglades system and its four geographic subregions: the northern estuaries, Lake Okeechobee, the greater Everglades, and the southern coastal systems. Indicator scores were developed and combined to communicate the Everglades' ecological condition to the public. Much of the SSR is structured around the Report Card results, with explanations of the indicators used and a discussion of monitoring data from the past 5 years.

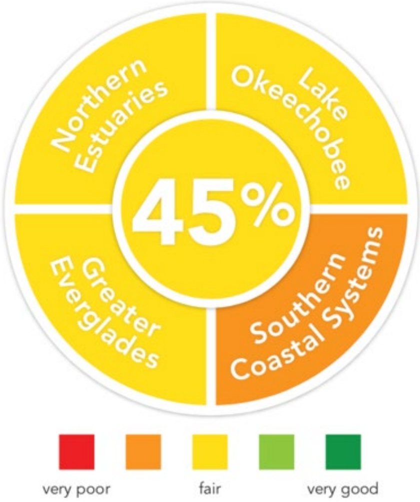


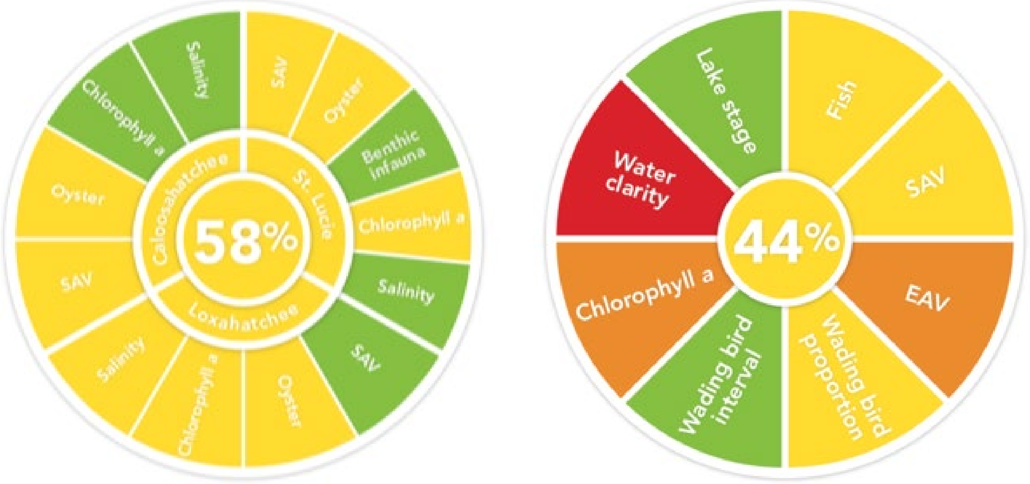
FIGURE 3-27 Overall score for the Everglades in the 2019 Report Card, which is calculated from regional scores ranging from "fair" to "poor." SOURCE: RECOVER, 2019.

The SSR and Report Card paint an alarming picture of the Everglades' condition, concluding that the Everglades ecosystem is in fair condition (Figure 3-27; Report Card scores for the four subregions of the Everglades are shown in Figure 3-28 and described in more detail in Box 3-2). The narrative accompanying the Report Card describes the Everglades as providing only minimal ecosystem functions, leaving it vulnerable to further ecological degradation, with essential ecosystem functions degraded and unsustainable. The South Florida Ecosystem Restoration Task Force came to a similar conclusion in their most recent System-Wide Indicators report (Brandt et al., 2018), stating that "none of the indicators have shown improvement over this reporting period and none have met restoration targets." The indicators reported on by the Task Force are a subset of the systemwide indicators used by RECOVER and confirm the findings of the SSR. The SSR goes on to say that "the Florida Everglades is struggling to survive in the face of sustained pressure from human activities and the increasing impacts of climate change." The poor to fair scores for the subregions indicate that the "anticipated ecological benefits of restoration are still to be realized." Although CERP project components implemented to date—Picayune Strand, C-111 Spreader Canal, and Biscayne Bay Coastal Wetlands—are beginning to deliver ecological benefits, they are relatively small in scale (compared to other pending CERP projects) and geographically disconnected, limiting the ability to detect benefits at a systemwide scale. Both the SSR and the Task Force call for continued, rapid action to implement the CERP and reverse the ongoing decline of the ecosystem to prevent impacts to tourism, recreation, and the economy of South Florida.

The creation of the Report Card shows a concerted effort by RECOVER to develop a means to effectively communicate progress on Everglades restoration to the public. A large amount of data was compiled and used to evaluate the status for each of the Everglades subregions and for the system as a whole—a valuable exercise that brings attention to a wealth of monitoring data. Results are presented in clear, easy-to-interpret graphics. However, some of the approaches used to analyze data and calculate

Report Card indicator scores lead to questionable findings. As an example, salinity in the St. Lucie Estuary fluctuates widely, with levels that are often lower or higher than the target salinity range. These extreme conditions have contributed to five major oyster die-offs in the St. Lucie Estuary. However, in calculating the salinity indicator, the high and low values are averaged, resulting in a “moderate” mean salinity and an indicator score of “good”—a far more optimistic assessment of the system than conditions on the ground warrant. Interestingly, the RECOVER team acknowledges this, saying that some indicator scores belie the high variability in the system. It seems likely that some of the Report Card scoring methods will need to be revised before the next SSR is produced.

a) Northern Estuaries **b) Lake Okeechobee**



c) Greater Everglades **d) Southern Coastal Systems**

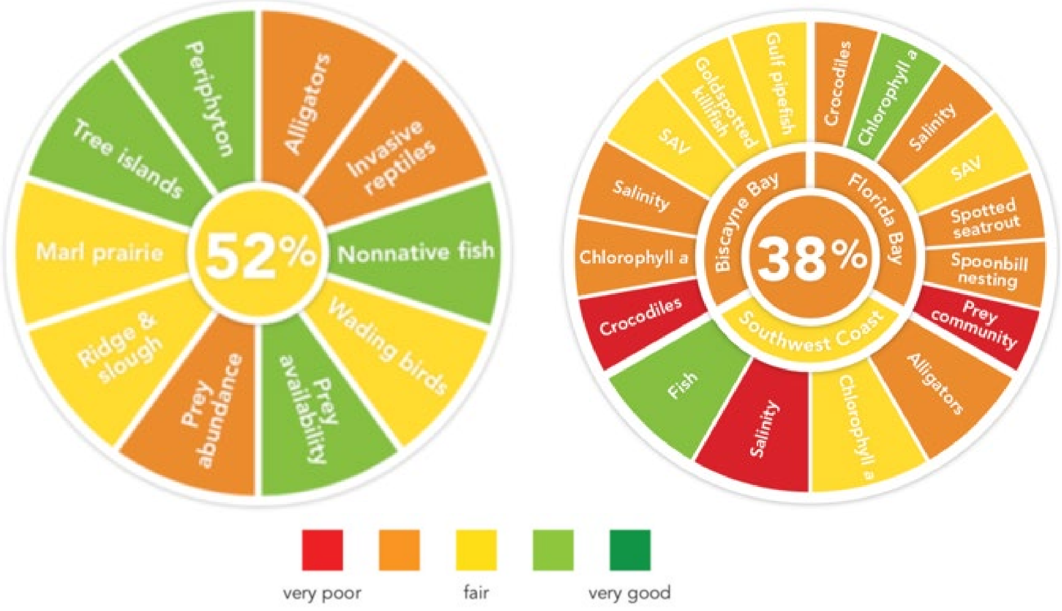


FIGURE 3-28 Scores for the Everglades subregions in the 2019 Report Card, showing (a) the northern estuaries, (b) Lake Okeechobee, (c) the greater Everglades, and (d) the southern coastal systems. The overall score for each region is calculated using the indicator scores assessed in that region as indicated by the wedges in each circle. The northern estuaries and southern coastal systems are further grouped by location. SOURCE: RECOVER, 2019.

BOX 3-2 RECOVER Report Card Condition Assessments for the Everglades Subregions

The Report Card scores four subregions of the Everglades: the northern estuaries, Lake Okeechobee, the greater Everglades, and the southern coastal systems (Figure 3-28). The northern estuaries earned a "fair" rating, due in large part to the negative impacts of periodic high freshwater flows from Lake Okeechobee and the resulting cycle of salinity perturbations that impact the estuaries and reduce survival of key species such as oysters. Oyster densities varied widely over the 5-year reporting period due to periods of extremely low salinity that led to large-scale oyster mortality. Fish and other benthic species were also affected by the combination of high freshwater flows, low salinity, and harmful algal blooms. RECOVER anticipates significant progress in restoring estuarine conditions once the projects to provide additional water storage to reduce harmful discharges to the estuaries are in place (see Chapter 5).

Indicator scores for Lake Okeechobee ranged from "poor" for water clarity to "good" for lake stage and wading bird nesting, with an overall score of "fair" (Figure 3-28b). Algal blooms were more frequent in 2012-2017 than in the previous 5 years, and cyanobacteria now dominate the lake algal community. In tandem, submerged aquatic vegetation (SAV) cover in the nearshore zone of the lake (where there is favorable SAV habitat) declined to a low of approximately 20,000 acres by 2017, well short of the goal of 50,000 acres. Fish, which support a large recreational fishery on the lake, also received a score of "fair," with declines in the recruitment of species such as black crappie and largemouth bass as SAV habitat decreased. Completion of the Herbert Hoover Dike and implementation of the new regulation schedule are predicted to help stabilize water levels. However, addressing degradation of the lake from harmful algal blooms is complicated by legacy phosphorus and nutrient loading from watershed runoff.

The greater Everglades received a "fair" rating, with indicator scores ranging from poor to good (Figure 3-28c). Key findings include that periphyton, a key indicator of oligotrophic conditions and the base of the Everglades food web, remained relatively constant. RECOVER (2019) presents a wealth of data on the ridge and slough landscape and tree islands and in the SSR they discuss the general links between water depths, microtopography, and ridge and slough structure, but they miss the opportunity to quantitatively link these factors in an assessment of ecosystem response. The ridge and slough landscape is acknowledged to be severely degraded over much of its extent, and is considered "fair." Tree islands are also severely degraded by impacts of high water levels, drought, fire, and invasive species, but only four tree islands were used to estimate their overall status, which resulted in the unexpectedly high score of "good." A larger sample size would reflect tree island condition more accurately. The anticipated changes in hydrology due to the Combined Operational Plan (COP; see Chapter 4) and CEPP are likely to reduces stressors on the greater Everglades, although restoration is now complicated by invasive reptiles such as the Burmese pythons that are increasing in numbers and area occupied.

The lowest overall score was earned by the southern coastal systems, which were deemed to be in "poor" condition (Figure 3-28d). Hydrology is the biggest driver of degradation, where low freshwater inflows lead to high salinity in both Florida and Biscayne Bays. Surprisingly SAV was scored as being in "fair" condition in both systems, despite extensive losses of seagrass beds due to hypersalinity (Florida Bay) and increasing nutrient and chlorophyll concentrations (Biscayne Bay; see Chapter 5). Monitoring data show that the status of key fauna, such as roseate spoonbill nesting and crocodile density, remain far from restoration goals.

The SSR is valuable in its compilation of data on different regions of the system, but it does not employ rigorous analytical methods that could illustrate trends and cause-and-effect relationships on restoration targets as CERP projects come online. As a result, the SSR fails to leverage the potential value of the data for adaptive management, project planning, and operation. The data are presented one variable at a time (e.g., chlorophyll a, algae, SAV, water levels), with little exploration of the relationships among various factors. Time-series data (typically for 2012-2017) are shown for many variables (e.g., wading bird nesting), but generally not in the context of restoration goals, and no analysis of long-term trends is performed (although some of this is presented in the Task Force Systemwide Indicators report [Brandt et al., 2018]). Older versions of the SSR contained more detailed analysis, but were sometimes criticized for being difficult for decision makers to digest. For example, NRC (2008) stated:

> The highly technical nature of much of the [2007] status report is a consequence of the focus on establishing baselines and change detection for the performance measures. As a result, the document is primarily of interest to scientists working on similar problems. Nonetheless, this type of analysis is critical to future assessments of changes in response to the CERP. For future system status reports with objectives that reach far beyond establishing baselines, this high degree of technical detail alone is unlikely to satisfy the needs of project managers and decision makers. Managers will need information relevant to the interim and ultimate restoration goals. To maximize the usefulness of future status reports for adaptive management, those reports should contain succinct summaries that clearly address whether the interim and longer-term goals are being met; if not, why; and what CERP operations or design changes are most likely to move ecosystem response closer to the interim goals.

In striving for more "user-friendly" documents, the 2019 SSR and Report Card (RECOVER, 2019) may have tipped the balance too far, by omitting critical analysis and synthesis of information to inform decision making. As increasingly more CERP and non-CERP projects are constructed and operated, CERP decision makers would benefit from analyses of long-term trends in monitoring data and more sophisticated analysis of multiple factors on system responses relative to restoration goals. There will be an increased need for information on the integrated system response so that decision makers and the public can understand the progress toward restoration goals and issues that may pose challenges toward meeting those goals to provide support for adaptive management.

Although the intent of the 2019 SSR is described as informing adaptive management, no recommendations are made to reverse the ongoing degradation and ensure that restoration is on track to meet interim goals. RECOVER (2019) acknowledges threats of climate change—particularly the impacts of sea-level rise, which has risen 11 inches at Key West over the past 105 years—as major influences on current and future system conditions that restoration planning must take into account. However, no guidance is given on what adjustments might be made in restoration planning and implementation in support of CERP goals. RECOVER could provide better support for adaptive management in future SSRs by providing specific recommendations of management options based on the analyses of monitoring data at a systems scale.

CONCLUSIONS AND RECOMMENDATIONS

State and federal funding for the CERP has increased significantly in recent years, which expedites the pace of project construction. Following a period of historically low state and federal funding for the CERP (2012-2016), state funding for the CERP has approximately doubled to more than $200 million per year. With federal CERP funding of $247 million in FY 2020, CERP funding has exceeded the original vision of $200 million per year from both the state and the federal government for the first time since the program's inception, and similar funding levels are anticipated in FY 2021. With this increased funding, CERP projects can be completed more quickly, resulting in faster restoration benefits and potentially mitigating ongoing ecosystem degradation.

The 2019 Integrated Delivery Schedule (IDS) does not effectively communicate likely restoration schedules and priorities consistent with realistic funding constraints. The 2019 IDS is based on the fastest possible construction schedule, given project dependencies, regardless of budget; the IDS assumes an average funding of more than $800 million per year for the first 5 years (nearly double the record budget in FY 2020). These assumptions may be acceptable for the purpose of explaining the benefits of increased funding, but they fail to support the difficult decisions that must be made when future funding is inadequate to meet these optimistic projections. CERP planners, in some simple alternative scenarios, assume that reduced funding simply stretches the timeline of the IDS proportionally. However, an optimal project prioritization is likely to be time dependent. In light of ongoing degradation of the system and peat collapse in the southern Everglades, it is probably unwise for all projects to be delayed equally with reduced funding. Rather, some projects should be prioritized based on project benefits in relation to ongoing system degradation. Uncertainty of funding (which occurs on a regular basis) necessitates evaluation of realistic and alternative levels of funding with consideration of the many time-dependent factors that may affect an optimal project prioritization. Development of the IDS could serve as a means to debate these challenging decisions with the multiple CERP agencies and stakeholders, as well as communicate the effects of schedule changes on the nature and timing of anticipated ecosystem benefits in the context of current ecosystem trends and ongoing pressures such as sea-level rise and harmful algal blooms.

Signs of restoration progress are evident from three CERP project increments operating to date, but limitations in monitoring, analysis, and communication of results have impeded quantitative assessment and communication of restoration benefits. Increments of the Picayune Strand and Biscayne Bay Coastal Wetlands (Phase 1) Projects and nearly all of the envisioned C-111 Spreader Canal (Western) Project have been operating for years, providing an important opportunity to learn from those results and communicate those incremental benefits to the public. Results from monitoring in Biscayne Bay Coastal Wetlands and Picayune Strand show positive trends and qualitative evidence of effects from implementation. Operations have been refined in the Biscayne Bay Coastal Wetlands Project to improve restoration outcomes (although some benefits remain limited by lack of available freshwater for the project). Assessments of restoration progress continue to be stymied by a lack of systematic analyses of quantitative results from early indicators of restoration relative to expected outcomes. Without this information, it is difficult to assess and communicate progress. This limitation applies to all three projects in some dimension, but is most evident in the C-111 Spreader Canal and Picayune Strand Projects, and improvements are needed. Understanding the challenges and opportunities for improved monitoring will lead to better restoration assessment.

Important opportunities for learning from monitoring at Picayune Strand are being missed that could inform current and future project management decisions across CERP and non-CERP agencies. Understanding the response of vegetation and fauna to restoration at Picayune Strand is hindered by invasive species and fire management. Widespread drainage of the area allowed invasive species to become established. Project managers should revisit the project goals and expectations, potentially shifting the ecological objectives toward improving conditions for desirable species and increasing resilience across the region to respond to climate change. Improved coordination across CERP and non-CERP agencies regarding fire management is needed. The monitoring plan should also be redesigned to support adaptive management of the project. An acknowledgment that hydrologic restoration is unlikely to replicate predrainage ecology could help agencies prioritize additional management actions, including fire management, necessary to achieve these revised goals.

STAs have been an effective approach to mitigate total phosphorus inputs to the Everglades Protection Area, but recent high concentrations in STA-2 effluent, several years after implementation of Restoration Strategies features for the central flow-way, raise concerns. The SFWMD 2018 Science Plan provides recommendations for evaluating factors to improve the performance of STAs that could be helpful in achieving lower effluent concentrations of total phosphorus and guide future operations. The SFWMD is planning to complete Restoration Strategies by 2025, and has until 2027 to demonstrate compliance. However, intensive efforts now to analyze and optimize performance and address shortfalls could help avoid delays in meeting the water quality criteria and delivering new water from CEPP. With heightened concerns about elevated nutrient loading and harmful algal blooms in the northern estuaries, the state is increasingly interested in water quality management of contaminants beyond phosphorus, especially for nitrogen. A preliminary analysis suggests limited removal of nitrogen by STAs. Therefore, research to improve understanding of nitrogen retention and loss in STAs and the potential to enhance nitrogen removal would inform decisions on the management of harmful algal blooms.

Phased implementation of major features of the Lake Okeechobee Watershed Restoration Project (LOWRP) will help accommodate the numerous uncertainties associated with aquifer storage and recovery (ASR), a technology that remains unproven at the proposed scale of deployment. The objectives of the LOWRP include reducing damaging discharges to the northern estuaries and improving lake levels in Lake Okeechobee. The tentatively selected plan proposes reduced aboveground water storage relative to the original CERP vision with the bulk of water storage provided by ASR wells. To address critical unknowns while moving forward with restoration, installation should proceed in increments of two to five ASR wells, with postinstallation monitoring to address outstanding questions related to the quality of recharged and recovered waters, ecological effects, and recovery efficiencies. Because aboveground storage provided by the wetland attenuation feature is small and its benefits are largely linked to the performance of ASR, the recently proposed schedule that postpones construction of the wetland attenuation feature until the ASR uncertainties are resolved is appropriate. Prior to construction, the contributions of the wetland attenuation feature to LOWRP's objectives of regulating lake water levels and estuary discharges should also be clarified and considered in the context of its cost.

The Everglades overall remain vulnerable overall to continuing degradation. The RECOVER 2019 System Status Report noted the dire condition of the Everglades ecosystem, with a "fair" rating of conditions systemwide and "poor" conditions in the southern coastal systems. Overall, the CERP projects operating to date have been limited and are disconnected on the landscape, leading to limited detectable responses of restoration at a systems scale. However, with several large reservoirs under construction in the northern everglades and the Combined Operational Plan in place in the southern part of the ecosystem, substantial restoration benefits are expected in the years ahead.

The System Status Report provides a useful compilation of data, but the lack of reporting of long-term trends and influencing factors limits its value to adaptive management and operational decision making. In the 2019 SSR, RECOVER compiles and presents a substantial amount of data to document the status and trends of the Everglades restoration for the period 2012-2017. Rigorous long-term trend analysis was not completed, making it more difficult to assess restoration progress and the causes of any observed changes. Synthesis of the findings of more rigorous multivariate analyses are needed in future system status reports to effectively leverage the results and develop improved systems-level understanding that can be used to inform future decisions. The Everglades Report Card, included as a stand-alone graphical summary of ecological conditions, represents a positive step in public communications, although methodological issues in some of the scoring approaches will need to be remedied in future reports.

4

Combined Operational Plan

The Combined Operational Plan (COP) is a new, comprehensive, integrated water control plan that defines the operations of the constructed features of the recently completed Modified Water Deliveries to Everglades National Park (Mod Waters) and C-111 South Dade projects (Figure 4-1; Figure 2-3). These non-CERP projects, authorized more than 25 years ago (Public Law 101-229; Public Law 104-303), are considered foundation projects for the Comprehensive Everglades Restoration Plan (CERP) because they alter the delivery and flow of existing water in ways that are critical to the CERP's capacity to deliver additional flow volumes and restoration benefits. As a regional operations plan, the COP supersedes the Everglades Restoration Transition Plan (ERTP) for operations in Water Conservation Area 3 (WCA-3) and its boundary with Everglades National Park and the 2012 Water Control Plan for the C-111 basin and, therefore, has implications for much of the central Everglades. Past reports of this committee have highlighted the ongoing degradation of the natural system in the central Everglades and the lack of restoration progress in this area (NRC, 2008, 2012a). Completion of Mod Waters and its operations plan is also required in the Water Resources Development Act of 2000 before federal funding can be appropriated for Central Everglades Planning Project (CEPP) construction. Therefore, the COP not only marks the completion of the essential first step toward restoring the central Everglades but also the beginning of the next important step—the CEPP. As such, the COP embodies a shift from a long phase of restoration planning to a new phase of implementing restoration actions and evaluating their success. In this respect, the COP is a microcosm of Everglades restoration and an early view of what system-level implementation of the CERP will entail, with many challenges, expectations, and opportunities to learn.

In this chapter, the committee reviews the COP, including its significance in the context of the history of the Everglades restoration, its expected restoration benefits, and the process by which it was formulated. The COP adaptive management and monitoring plan is also assessed.

HISTORICAL BACKGROUND TO THE DEVELOPMENT OF THE COP

Controversy over water management in the domain of the COP has driven efforts to restore the Everglades, including the development and implementation of Mod Waters, C-111 South Dade, and the CERP. Adverse changes to the natural system in this area and associated legal action have also propelled restoration. The following sections describe some of the key issues influencing restoration efforts in Shark River Slough through Mod Waters, and Taylor Slough and eastern Everglades National Park through the C-111 South Dade project, to provide context for understanding COP benefits.

Shark Slough and Mod Waters

Prior to the construction of the Water Conservation Areas, approximately two-thirds of the flow into Shark Slough came through Northeast Shark River Slough based on the natural gradients in the system (Figure 4-2). After development of the Water Conservation Areas in the mid-1960s, conditions in Western Shark River Slough became much wetter (90 percent of total flow) and Northeast Shark River Slough much drier (10 percent of total inflow; Figure 4-3), producing a myriad of adverse ecological effects. For example, tree islands in Northeast Shark River Slough were lost because of peat oxidation caused by fires and lack of water (Sklar and van der Valk, 2012). These ecological impacts were recognized, and a series of actions were taken in the 1970s and 1980s in an attempt to alleviate the effects of an extended drought on Everglades National Park and reduce environmentally damaging releases of water into Western Shark River Slough. These actions included regulations requiring delivery of more water to Everglades National Park, changes in flow management, and enlargement of canals, but they proved to be inadequate (Table 4-1). For example, the Experimental Water Deliveries program (1983-1999) was able to deliver only a slight increase in flows into Northeast Shark Slough (Figure 4-3) due to flood mitigation constraints protecting residences in the 8.5 square-mile area (Figure 4-1). Thus, conditions remained too wet in Western Shark River Slough compared to historic conditions, and too dry in Northeast Shark River Slough (Van Lent et al., 1999), and ecological degradation continued.

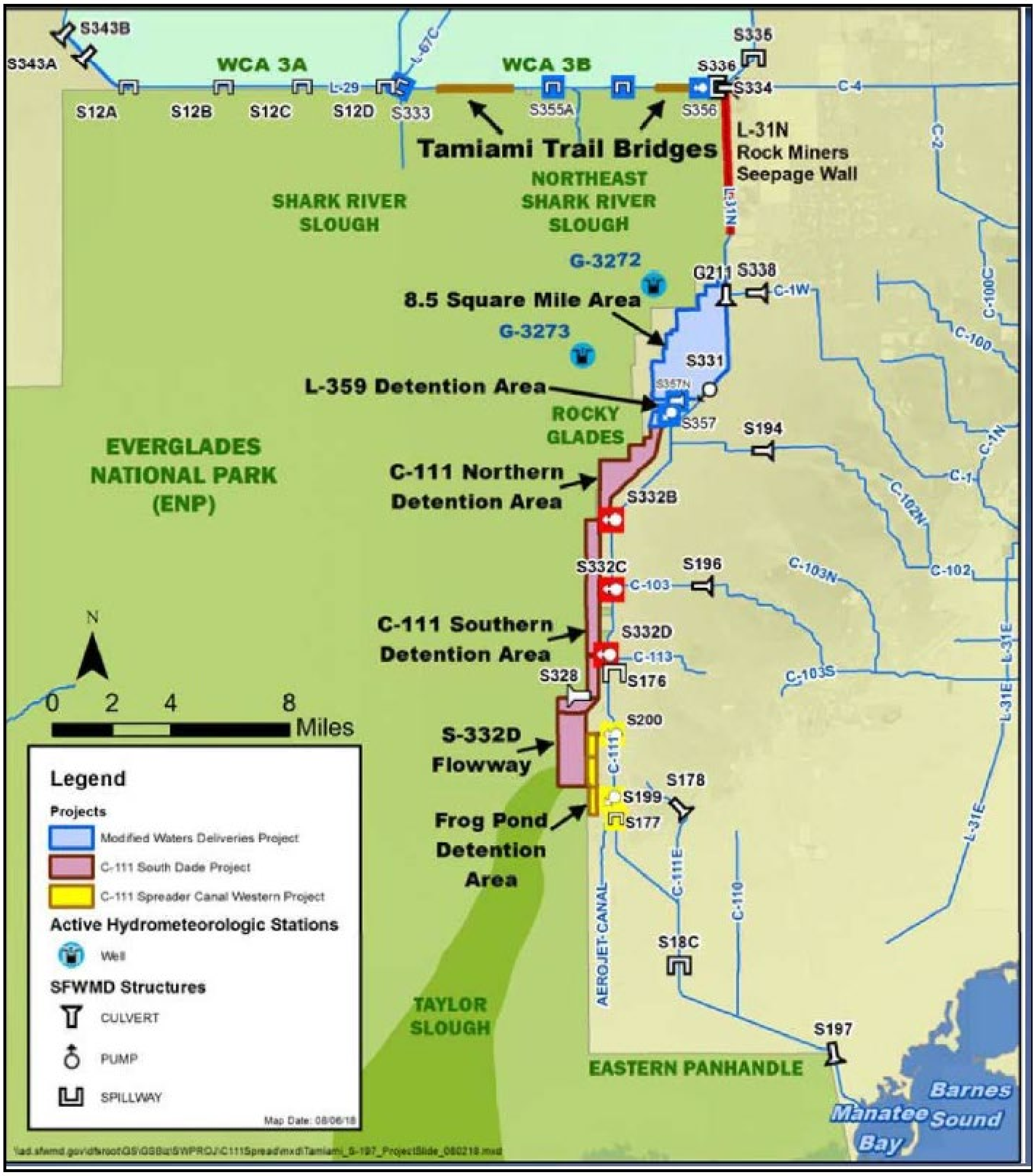


FIGURE 4-1 The non-CERP Modified Water Deliveries and C-111 South Dade, the Limestone Product Association seepage barrier (dark red in the figure), and the CERP C-111 Spreader Canal Western Project all are expected to contribute to increased flows in Northeast Shark River Slough and Taylor Slough in Everglades National Park. SOURCE: USACE, 2020b.

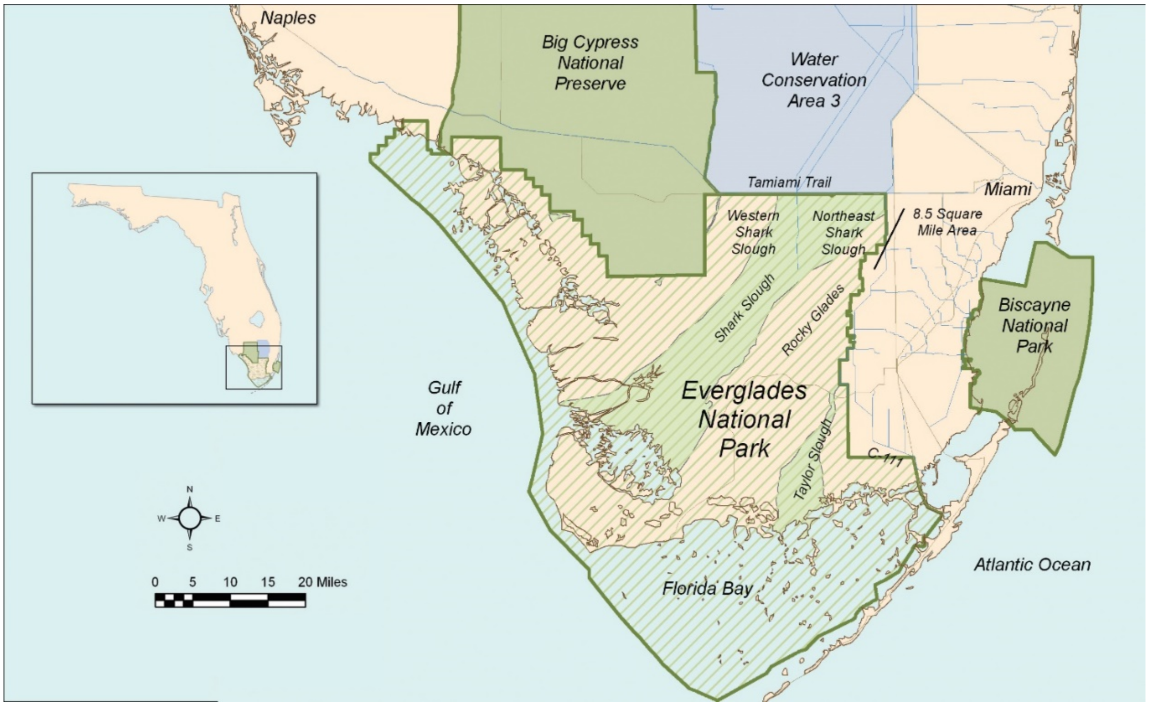


FIGURE 4-2 Western Shark River Slough, Northeast Shark River Slough, and Taylor Slough. SOURCE: https://www.nps.gov/ever/learn/nature/upload/RestorationFactSheet%20Lo%20Secure.pdf.

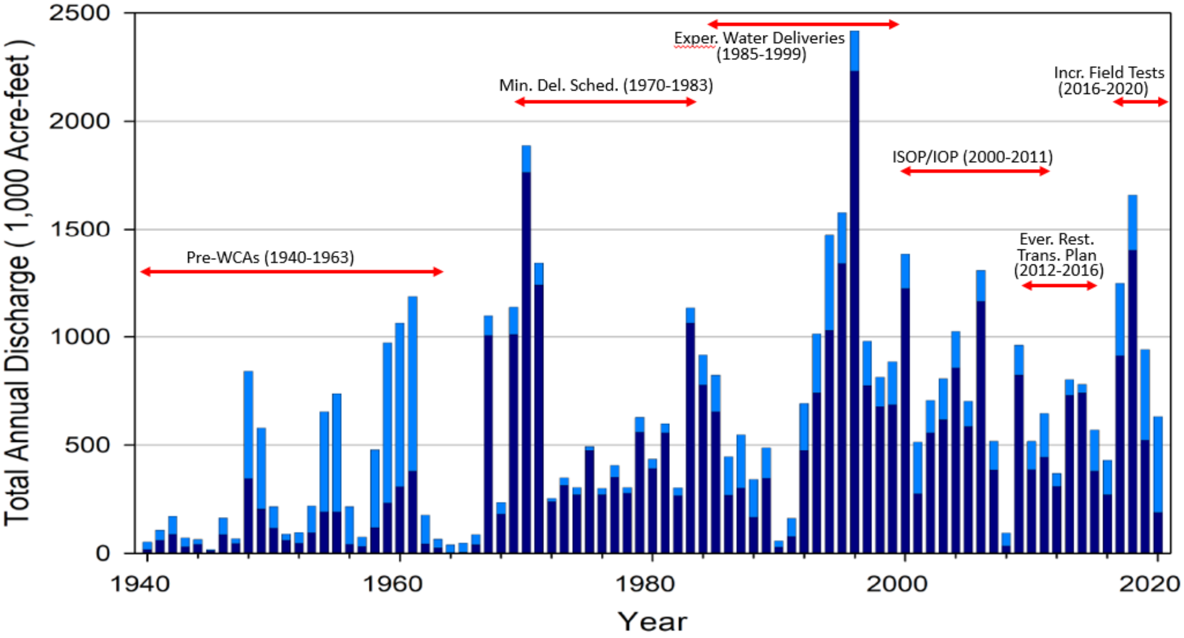


FIGURE 4-3 Water discharges into Everglades National Park by way of Western Shark River Slough (dark blue) and Northeast Shark River Slough (light blue), showing how water was diverted to Western Shark River Slough at the expense of Northeast Shark River Slough, with some return to Northeast Shark Slough more recently. The graph indicates the operational schedules that governed water flows through these pathways from 1940 to 2020. SOURCE: R. Johnson, National Park Service, personal communication, 2020.

The limitations of this water management regime resulted in a crisis when record high rainfalls subsequent to Hurricane Andrew in 1992 and large regulatory releases through the S-12 structures into West Shark River Slough in 1993-1995 nearly extirpated subpopulation A of the endangered Cape Sable seaside sparrow (CSSS), which had formerly been the largest of the six CSSS subpopulations (Figure 4-4). In response to these impacts on the CSSS, the U.S. Fish and Wildlife Service (FWS) issued a Jeopardy Opinion on the Experimental Water Deliveries Program in 1999, effectively ending the program and necessitating the development of new water management. That the CERP was authorized immediately following this crisis is not coincidental.

The Everglades National Park Protection and Expansion Act of 1989 authorized Mod Waters and directed the U.S. Army Corps of Engineers (USACE) in consultation with the Department of the Interior to improve water deliveries into Everglades National Park and, to the extent practicable, take steps to restore natural hydrologic conditions in the park while maintaining flood protection of and water supply to the built environment (Public Law 101-229; NRC, 2008). The changes to hydrology outlined in the Mod Waters plan (USACE, 1992) to meet this mandate were much the same as those required to address the legal issues with the endangered CSSS, including shifting flows from Western to Northeast Shark River Slough. Thus, the ecosystem restoration goals of Mod Waters aligned with the legal requirements for endangered species management subsequently imposed in 1999.

TABLE 4-1 Timeline Leading to Initial Authorization and Preliminary Plans for the Mod Waters Project

Date	Event	Purpose
1960s	Extended historic drought affects Everglades National Park (ENP)	
1968	ENP South Dade Conveyance System (Flood Control Act)	Enlargement of the L-31N and C-111 canals to supplement water deliveries to South Dade and ENP
1970	Minimum Water Delivery Schedule (Public Law 91-282)	Required a minimum of 315,000 acre-feet of water deliveries to ENP each year, with a fixed monthly allotment[a]
1983	ENP Seven-Point Plan issued	ENP recommendations to reduce the impacts of high S-12 regulatory flows on West Shark River Slough [b]
1983-1999	Experimental Water Deliveries Program (Public Law 98-181)	Test different water delivery schedules to restore more normal flow, especially in Western and Northeast Shark River Slough
1989	ENP Expansion Act (Public Law 101-229)	Acquire 109,000 acres in Northeast Shark River Slough; authorized Modified Water Deliveries and C-111 Projects
1992	General Design Memorandum (GDM) for Mod Waters finalized (USACE, 1992)	Restore historic flow-way between WCA-3A, WCA-3B, and Northeast Shark River Slough and relieve high flows from WCA-3A to Western Shark River Slough. The plan aimed to deliver 55 percent of the total flow volume east of L-67 to reflect historic flow paths

[a] 260,000 acre-feet delivered to West Shark River Slough, and 55,000 acre-feet delivered to Taylor Slough and Eastern Panhandle basins.

[b] The seven points included (1) fill in the L-28 and L-67 Ext. canals and remove the levee (promote sheet flow); (2) gap the L-67A and L-67C levees (promote sheet flow and restore flows through WCA-3B); (3) redistribute West Shark Slough inflows along the full length on the Tamiami Canal (L-28 to L-30); (4) establish a bimonthly water quality monitoring program for ENP (Memorandum of Understanding with the U.S. Army Corps of Engineers/South Florida Water Management District); (5) defer implementing a proposed drainage district in the East Everglades; (6) field test a rainfall-based water delivery schedule for the WCAs and ENP; and (7) suspend minimum water delivery schedule (Light and Dineen, 1994).

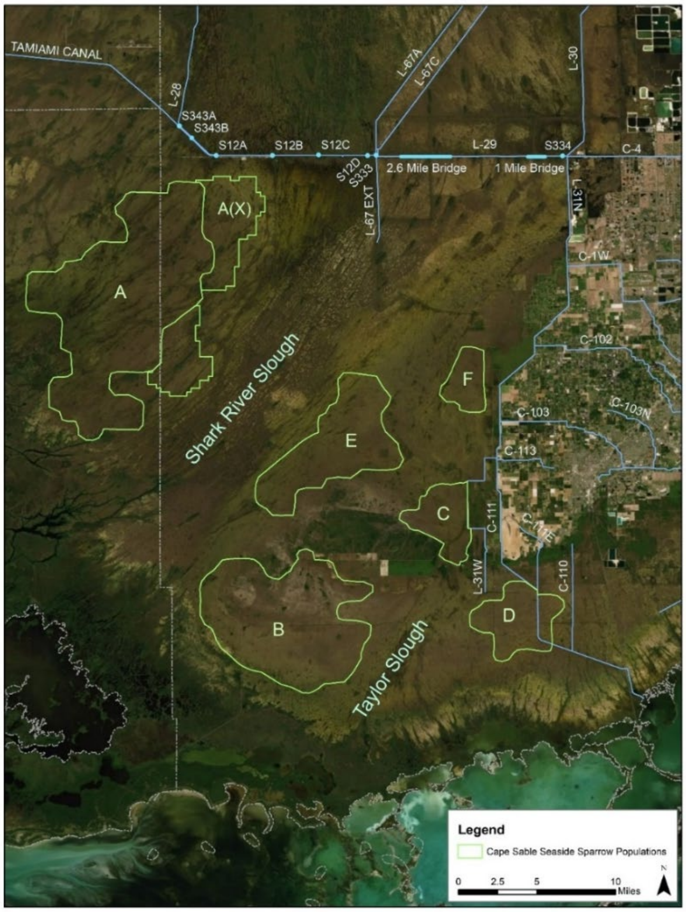


FIGURE 4-4 The Cape Sable seaside sparrow exists in six subpopulations, which are all located in Everglades National Park. SOURCE: Meyers, 2019.

Following the demise of the Experimental Water Deliveries Program and while construction of Mod Waters continued, water management at the boundary of WCA-3A and Everglades National Park was governed by interim operational plans[1] to protect the CSSS. These operations plans suffered from the same flood risk management constraints that compromised the Experimental Water Deliveries Program and thus fared little better in increasing flows to Northeast Shark River Slough (Figure 4-3). In addition, with limited water conveyance capacity into Northeast Shark River Slough, closure of the S-12s to protect the sparrows adjacent to Western Shark River Slough under the interim operational plans exacerbated high water levels during wet conditions in southern WCA-3A. Thus, these plans both failed to significantly address ecosystem degradation in Everglades National Park and worsened problems in WCA-3A, producing adverse effects on ridge-and-slough topography, tree islands, and another endangered bird, the snail kite. Furthermore, constraints on flows to the south during high water conditions necessitated release of water from Lake Okeechobee through the northern estuaries, resulting in adverse ecological effects there.

Analyses indicated that the systemwide hydrology envisioned in the CERP would provide for both Cape Sable seaside sparrows and snail kites, as well as other avian species that are conservation priorities, such as roseate spoonbills, wood storks, and other wading birds (SEI, 2007). In keeping with this vision, a multispecies approach to integrate the needs of these avian species in WCA-3A and Everglades National Park (FWS, 2010) was incorporated into new water management operations—the

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[1] The Interim Structural and Operational Plan was implemented in 2000 followed by the Interim Operational Plan (IOP) in 2002.

ERTP—implemented in 2012. Like the operations plans that preceded it, the ERTP attempted to improve hydrologic conditions in the central Everglades within the constraints of existing infrastructure, specifically by shifting flow from Western to Northeast Shark Slough, increasing flows into Everglades National Park, and reducing ponding of water in southern WCA-3A. These hydrologic goals are consistent with those of Mod Waters and the CERP. However, the ERTP proved little more effective in reaching these objectives than previous plans, and conditions in Western Shark Slough continued to be too wet while Northeast Shark River Slough remained too dry (Figure 4-3). In 2016, the U.S. Fish and Wildlife Service issued a Jeopardy Opinion on the impact of the ERTP on the CSSS (FWS, 2016a).

As of 2016, little progress had been made in restoring the central Everglades through operational refinements using existing infrastructure. The COP, which employs the features constructed under Mod Waters and C-111 South Dade, is scheduled to go into effect in August 2020 and is expected to be a major step toward restoring the central Everglades, making substantive progress toward the goals of the CERP for this region. Two features of Mod Waters are especially critical to the capacity of the COP to achieve this. First, Tamiami Trail was raised to a design high water level of 8.5 ft National Geodetic Vertical Datum of 1929 (NGVD) in the L-29 canal (compared to 7.5 ft under prior conditions). This increased elevation, combined with the 1-mile bridge constructed through Mod Waters and the 2.6-mile western bridge constructed through Tamiami Trail Next Steps, enables increased flows into Northeast Shark River Slough and Everglades National Park. Second, seepage management and flood mitigation features, including the S-356 pump station, acquisition of roughly one-third of the 8.5-square-mile area, and construction of a levee to protect the remainder of this area from flooding (Figure 4-1), were constructed to limit flood risk management constraints on the eastern boundary. The COP represents not only the final action that completes Mod Waters but also is envisioned to be the solution to the legal issues related to protection of endangered CSSS that have plagued water management at the boundary of WCA-3A and Everglades National Park for 25 years (FWS, 2016a).

C-111 South Dade and Taylor Slough

The C-111 canal was constructed in the 1960s as part of the Central and Southern Florida Project to provide flood protection to agricultural lands east of Everglades National Park. The canal system also drained the eastern side of Everglades National Park, causing reduced hydroperiods and flows in Taylor Slough and high freshwater canal discharges into Manatee Bay and Barnes Sound (Figure 4-1). The reduction in flows through Taylor Slough was exacerbated in the 1980s by reductions in the L-31N canal stage to reduce flooding in the lands to the east (Figure 4-5). Adverse effects of altered hydrology included reduced salinity in Manatee Bay and Barnes Sound due to freshwater discharges, and high salinity in Florida Bay and degradation of marl prairies inhabited by Cape Sable seaside sparrows due to reduced inflows from Taylor Slough (Figure 4-4). The poor performance of the CSSS subpopulations near Taylor Slough was a component of the Jeopardy Opinion issued for the ERTP in 2016 (FWS, 2016a).

In 1994, the C-111 South Dade project was developed to include environmental restoration among the objectives of water management in the C-111 basin (USACE, 1994). The objectives of the C-111 South Dade project are to reduce freshwater canal discharges to Manatee Bay and Barnes Sound and restore hydrologic conditions in Taylor Slough and the Eastern Panhandle of Everglades National Park, thereby increasing overland flows to northeastern Florida Bay, while continuing to honor flood risk management constraints for the agricultural lands east of the park (USACE and SFWMD, 2020c). Seepage reduction is the primary means to accomplish the project objectives and is accomplished by constructing large detention areas and pump stations to create a hydraulic ridge between Everglades National Park and the agricultural lands to the east (Figure 4-1). The C-111 (Western) Spreader Canal CERP project (see Chapter 3 and Figure 4-1) extends the hydraulic ridge southward and was functionally completed in early 2012, but its operations are not impacted by the COP.

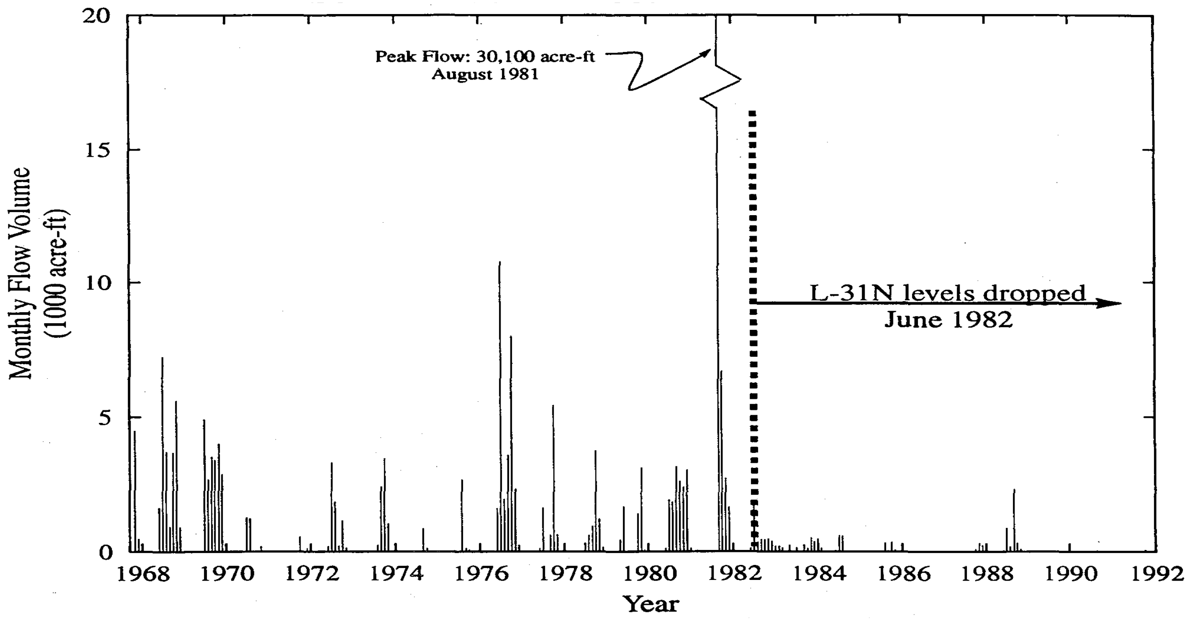

FIGURE 4-5 Changing surface water flows in Taylor Slough measured at Context Road near Homestead, Florida, between 1967 and 1992. The operational change in 1982 in the adjacent L-31N canal represents the lowering of the S-176 design optimum from 5.5 feet NGVD to 4.3 feet. Other factors, such as climate variability, may have contributed to the observed changes. SOURCE: Van Lent et al., 1993.

DEVELOPMENT OF THE COP

Once finalized, the COP will serve as the operational plan for the features of both recently completed pre-CERP foundation projects, Mod Waters and C-111 South Dade, superseding past basin-specific operational plans. The COP represents the first opportunity to employ all of the features of these projects to accomplish their objectives.

The stated objectives of the COP are primarily ecological (see Box 4-1). Achieving these objectives is subject to a variety of constraints, of which two related to flooding were of primary concern. In the 8.5 square-mile area the constraint required no increase in periodic flooding of lands within the levee over pre-Mod-Waters baseline conditions, based on the Everglades National Park Protection and

BOX 4-1 COP Objectives

The COP Environmental Impact Statement (USACE, 2020b) identifies five project objectives:

“(1) improving water deliveries (timing, location, volume) into ENP given current C&SF infrastructure;

(2) maximizing progress toward restoring historic hydrologic conditions in Taylor Slough, the Rocky Glades and the eastern Panhandle of ENP;

(3) protecting the intrinsic ecological values associated with Water Conservation Area (WCA) 3A and ENP;

(4) minimizing damaging freshwater flows to Manatee Bay/Barnes Sound through the S-197 structure and increasing flows through Taylor Slough and coastal creeks; and

(5) include consideration of cultural values and tribal interests and concerns within WCA 3A and ENP.”

Expansion Act of 1989 (Public Law 101-229). Additionally, the COP must not exceed the level of flood risk defined as the 1994 baseline condition for the C-111 Basin (east of the L-31 canal), which was set forth in the USACE Environmental Impact Statement (USACE, 1994) and codified in the Water Resources Development Act of 1996 (Public Law 104-303). The formulation of the COP also considers "concerns" and "planning considerations." Concerns are aspects of the system that water managers want to maintain or improve upon rather than adversely affect. These include water supply, groundwater, fish and wildlife, and recreation. Planning considerations included ensuring compatibility of the COP with CEPP, maintaining multispecies objectives established in the ERTP, maintaining water quality, and exploring opportunities to enhance flood mitigation, among others. Planning considerations and concerns were addressed in a variety of ways that differed greatly in the level of analysis and methodology.

Field Testing

The development of the COP was informed by data gathered during a period of incremental operational testing, beginning in 2015 (see Box 4-2). The incremental field tests were designed to assess the hydrologic response to operations of the Mod Waters structures, including the capacity of the new seepage control infrastructure around the 8.5 square-mile area to accommodate higher flows in Northeast Shark River Slough. Key features of the field tests were relaxing existing flood risk management constraints on gage G-3273 related to flow from WCA-3A into Northeast Shark River Slough (Figure 4-1) and incrementally increasing the stage in the L-29 Canal from 7.5 feet NGVD in Increment 1 to 8.5 feet NGVD in Increment 2. Operations were interrupted repeatedly during the field tests by temporary emergency deviations due to high-water conditions, such that the system operated as specified for the different increments only 54 percent of the time from its initiation through April 2019.

These field tests revealed difficulties in flood management in the 8.5 square-mile area, which led to modifications of operations of subsequent increments (Box 4-2). Extending the duration of operations above 8.3 feet NGVD (Increment 2) requires demonstrating that flood risk management constraints can be maintained for Tamiami Trail roadway protection and in the 8.5 square-mile area. USACE (2020b) noted that compliance with this constraint has not yet been demonstrated. This impasse and the modifications to operations that occurred in Increment 1 due to flooding indicate that flood risk management for the 8.5 square-mile area remains, as it has for decades, a large constraint on flow to Northeast Shark River Slough, despite the new infrastructure added in Mod Waters.

Process for Selecting Among Alternatives

The development of the COP followed the standard USACE planning process. The planning approach employed used a combination of modeling, elicitation from experts, inference based on recent historical observations of flow, and, in some cases, physical experimentation. Alternatives were developed in a series of workshops, beginning with a set of extreme alternatives that either prioritized environmental restoration objectives or prioritized flood risk management. Learning from incremental field testing (Box 4-2), which occurred since 2015 amidst substantial variability in water levels, including high-water years, also informed the development of alternatives. Using model-based analysis, planning objectives, constraints, and planning considerations were applied to score the initial list of candidates and screen alternatives. Three alternatives emerged (Alternatives K, L, and N), which, respectively, emphasized flood mitigation for South Dade, providing the most flows into Northeast Shark River Slough, and balancing each. Results were reviewed and evaluated by subteams representing ecological, flood risk, water quality, and water supply issues.

BOX 4-2 Field Testing of the Combined Operational Plan

Field testing and monitoring were used to evaluate the hydrologic response to the proposed new operations.

- **Increment 1** (2015-2017) relaxed existing constraints on gage G-3273 related to flow from WCA-3A into Northeast Shark River Slough, while maintaining the L-29 Canal at the stage of 7.5 feet National Geodetic Vertical Datum of 1929 (NGVD). Another objective of Increment 1 was to test seepage control provided by the S-356 pump station, which was designed to return seepage water back into Northeast Shark River Slough from the L-31N Canal. Increment 1 testing also included reduced flow to South Dade from S-331 and conditional increased use of S-197 (USACE, 2015). Increment 1 was initiated in October 2015, but was interrupted from December 2015 to December 2016 by flood management operations and an emergency deviation due to high water levels in WCA-3A and the time required for recovery. During this deviation, water levels in the L-29 Canal exceeded 8 feet NGVD for more than 2 months.
- **Increment 1 Plus** (2017-2018) was an update to Increment 1 and incorporated the lessons learned from the emergency deviation and the Reasonable and Prudent Alternative from the July 2016 Everglades Restoration Transition Plan Biological Opinion (FWS, 2016a). Increment 1.1, implemented in March 2017, incorporated these changes while maintaining an L-29 Canal stage of 7.5 feet NGVD. Increment 1.2 raised the L-29 Canal stage to 7.8 feet NGVD, following completion of C-111 South Dade Contract 8 flood management features. A temporary deviation was implemented between June 28, 2017, and January 2018 to maximize high water discharges out of the WCAs.
- **Increment 2** (2018-2020) was approved in February 2018 and implemented in July 2018. Increment 2 allowed the L-29 Canal to reach a maximum stage of 8.5 feet, further relaxing constraints set by G-3273 (USACE, 2020b; R. Johnson, NPS, personal communication, 2018). When enacted, operation of the L-29 canal above 8.3 feet NGVD was limited to 90 days per water year due to concerns from the Florida Department of Transportation about potential impacts on the Tamiami Trail roadbed, although some modifications were made due to high water levels and enhanced monitoring. Impacts to the roadbed were evaluated as part of Increment 2. These stage constraints are expected to be removed when the road is raised as part of the Tamiami Trail Next Steps project.

The performance of a narrowed list of COP alternatives was compared in three rounds of hydrologic modeling and compared against an existing-conditions baseline (ECB19RR). The baseline represents the approved operational plan at the time of implementation of the COP. Under this baseline (ECB19RR), the Mod Waters and C-111 South Dade infrastructure is in place, and it incorporates operational enhancements mandated by the 2016 ERTP biological opinion that were evaluated in the Increment 1.1 and 1.2 field tests. Alternatives K, L, and N were evaluated in round one, and in the second round, a refined set of three alternatives (N2, O, and Q) were compared (see USACE [2020b] for details). Each of these alternatives satisfied constraints identified at the outset of the planning process, while differing with respect to rules for water deliveries to Everglades National Park, flood mitigation operations within the 8.5 square-mile area, provision of flows to Taylor Slough, operation of S-197, and protocols during high-water conditions within WCA-3A. Modeling in the second round included six ecological models in addition to the hydrologic models used in round one. In a third round, additional model-sensitivity runs were performed to further refine the alternatives, leading to the development of Alternative Q+, the preferred alternative.

The process-related decisions for evaluating a preferred alternative include the selection of performance metrics, the models used for evaluating the alternatives, the scenarios over which alternatives will be evaluated, and the criteria for selecting a preferred alternative based on the modeling results. The team used a consultative process to transparently communicate their approach and invited comment on their evaluations from federal agencies, affected Indian Tribes, state and local agencies, and other interested parties. Two sets of performance metrics were selected, one by an ecological subteam and one by a flood risk subteam, and these included systemwide metrics previously used by RECOVER and others previously used by the CERP. The relationship between the COP project objectives and the performance metrics, however, is not entirely clear. For example, the COP objectives (Box 4-1) are all ecological, but flood risk management over and above that required to meet constraints was a factor used extensively in alternative development and figured prominently in the evaluation of alternatives. The seemingly overlapping definitions of planning objectives, constraints, and considerations used to evaluate alternatives makes it difficult to understand if objectives remained the primary factors in alternative selection or were subjugates to constraints or considerations unrelated to the objectives.

Established regional hydrologic models (Regional Simulation Model [RSM] application for the Glades-Lower East Coast Service Area [RSM-GL]) was used to estimate the performance metric values for each alternative for a historical 41-year simulation period (1965-2005). For some performance measures, the Miami-Dade [MDRSM] model was applied to examine in higher spatial and temporal detail performance in 3 years—a wet (1995), a dry (1989), and an average year—and compared to baselines related to previous flood protection agreements. Performance of alternatives was not evaluated for changes in precipitation frequency and occurrence, either due to natural variability or climate change, or the implications of sea-level rise that might occur in the period of implementation of the COP. The model results have not been transparently compared to observations in the COP analysis, so the error and uncertainty inherent in the model output relative to the effect of COP alternatives is unclear.

The selection of the preferred alternative involved iterative improvement of intermediate alternatives based on multiobjective trade-off analysis that used a number of the performance metrics to compare the performance of the alternatives. The trade-offs between objectives were not presented and the process for selecting among objectives not explicitly reported, nor was the weight given to planning considerations clear. In particular, while achieving a mandated baseline level of flood risk management was a clear constraint, the planning consideration of enhanced flood mitigation also appeared to play an important, unspecified role, with preference for plans that provided additional flood risk management benefits.

The Preferred Alternative

The preferred Alternative Q+ incorporates various operational features to increase the flow of water across the northern boundary of Everglades National Park. The details of the operational plan are outlined in USACE (2020b, Table 2-2). Among the operational changes, water deliveries from WCA-3A to Everglades National Park will be regulated according to the newly developed Tamiami Trail Flow Formula (TTFF; SFWMD, 2019b). The TTFF is a multiple linear regression that predicts target water releases at S-12C, S-12D, and S-333 from WCA-3A into Everglades National Park from state variables of the system (previous flow, precipitation, potential evapotranspiration, and storage levels in WCAs). The peak stage in the L-29 Canal will be 8.3 feet, with the added provision of operating L-29 at 8.5 feet for up to 90 days per calendar year. The preferred alternative includes the capability to further extend and/or remove the cumulative duration criteria for operating the L-29 canal above 8.3 feet NGVD, while continuing to adhere to the maximum operating stage limit of 8.5 feet NGVD, Tamiami Trail roadway protection, 8.5 square-mile area flood mitigation, and consideration of low-water stages within WCA 3A. The preferred alternative removes the G-3273 stage constraint that formerly triggered cessation of S-333 discharges into Everglades National Park. While enhancing flow into Northeast Shark River Slough, Alternative Q+ reduces flows into Western Shark River Slough and incorporates the reasonable and prudent action of the 2016 ERTP biological opinion for extended closure periods of the S-12 structures to mitigate high-water conditions that threaten CSSS habitat (FWS, 2016a).

To the east of the park under the preferred plan, stages in the C-111 Canal and in L-31 reaches south of the 8.5 square-mile area will be lowered compared to 2002-2015 operating levels. Water-detention areas will no longer have operational stage constraints; when filled, the detention areas create a hydraulic ridge to lower seepage losses from Everglades National Park and increase water flows in Taylor Slough. Alternative Q+ also modifies the operational criteria for the C-111 structure S-197 for the purposes of reducing freshwater discharges to Manatee Bay.

BENEFITS EXPECTED FROM THE COP

The COP Environmental Impact Statement (EIS; USACE, 2020b) estimates benefits by comparing conditions under Alternative. Q+ to an existing-conditions baseline (ECB19RR), which is intended to represent the approved operational plan at the time of implementation of the COP in 2020. Because infrastructural and operational improvements from Mod Waters and C-111 South Dade are embedded into ECB19RR, USACE (2020b) only quantifies a portion of the benefits provided by this infrastructure. For example, model-simulated, average annual flows across a transect in Northeast Shark River Slough were three times greater under ECB19RR than during pre-ERTP (prior to 2012) conditions, while overland flow in the headwaters of Taylor Slough were nearly twofold greater for ECB19RR than for pre-ERTP (Figure 4-6) (W. Wilcox, South Florida Water Management District [SFWMD], personal communication, 2020). In the examples shown in Figure 4-6, the baseline accounts for roughly half of the benefit projected for the COP alternatives plotted relative to pre-ERTP conditions. No information is available for COP benefits from Alternative Q+ relative to pre-ERTP conditions; therefore, the benefits described in the EIS and summarized in the next paragraphs should be considered an underestimate of the full hydrologic lift provided by the recently constructed Mod Waters and C-111 South Dade infrastructure that falls under the scope of the COP. Although the methodology for calculating benefits is reasonable for selecting a preferred alternative, the agencies missed an opportunity to broadly communicate the benefits derived from several decades of restoration investments.

Hydrologic Benefits

Implementation of Alternative Q+ is predicted to increase average annual flows across Tamiami Trail and into Everglades National Park by 28 percent relative to the no-action alternative (ECB19RR), while increasing the proportion of flow that enters Northeast Shark River Slough (east of S-333) from 58 to 77 percent. The increase in flows across the trail will be accompanied by longer hydroperiods within the Everglades National Park, particularly in Northeast Shark River Slough (Figure 4-7). Shifting more water to the east will lead to a closer approximation of historic flow patterns and is expected to improve ecological conditions in Northeast Shark River Slough. Water deliveries from WCA-3A to Everglades National Park are expected to yield the greatest improvements during extremely dry conditions, when flows to the park would cease under ECB19RR (Figure 4-8).

Alternative Q+ provides additional operational flexibility through inclusion of special management protocols triggered by exceedance of an extreme high-water limit in WCA-3A. Since 2015, unusually wet conditions have forced the USACE to seek two emergency deviations from the 2012 water control plan, which required the State to gain permission from potentially impacted land owners to flow additional water across their property and to conduct an environmental assessment of the effects of the flow deviation. The extreme high-water limit in the COP is intended to streamline the process required to implement actions to respond to high-water conditions, alleviating additional National Environmental Policy Act (NEPA) reviews. It also allows flows to bypass Everglades National Park and be routed through the South Dade Conveyance System and released through S-197 to Manatee Bay. Although expected to be triggered infrequently, the extreme high-water limit would help protect the WCA-3A perimeter levee system, reduce the risk of flooding to hurricane-evacuation routes, and lower the threat of high-water conditions to wildlife and tree islands inside WCA-3A.

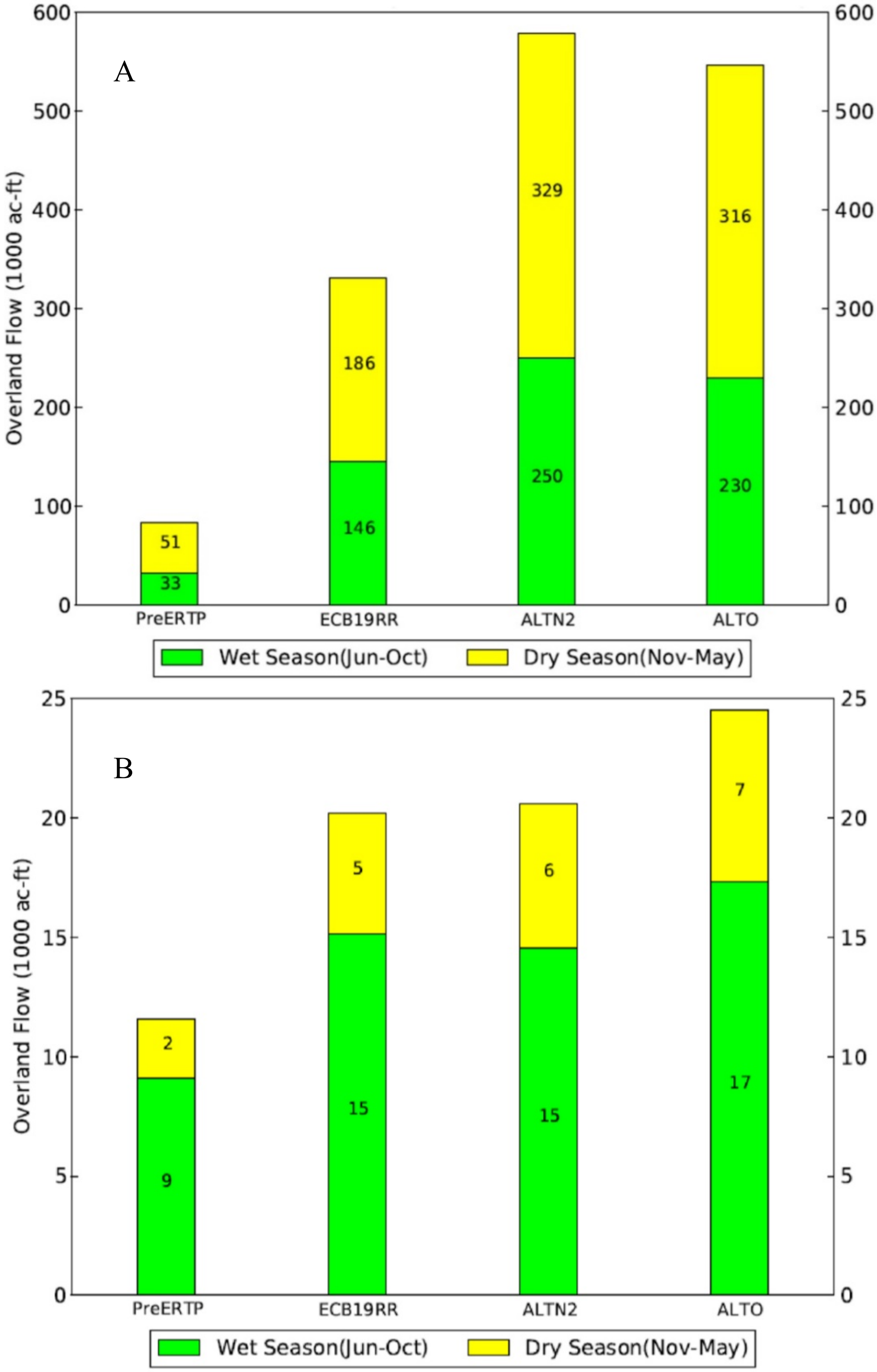

FIGURE 4-6 Average annual flows projected in wet and dry seasons in (A) transect 18 in Northeast Shark River Slough and (B) transect TSH1 in the Taylor Slough headwaters for two early COP alternatives (N2 and O) relative to pre-ERTP conditions (pre-2012) and the COP baseline (ECB19RR). The graphs show the sizable increase in flow between pre-ERTP conditions and the COP baseline, reflecting benefits attributable to the Mod Waters and C-111 South Dade infrastructure not captured in the COP Environmental Impact Statement analysis. SOURCE: W. Wilcox, SFWMD, personal communication, 2020.

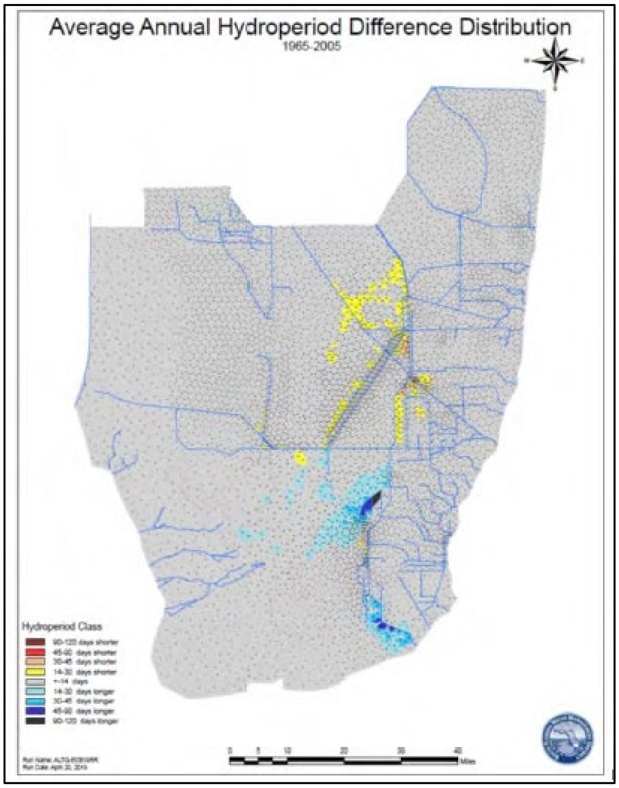

FIGURE 4-7 Difference in average annual hydroperiods for Alternative Q and the existing conditions baseline. Analyses of model sensitivity simulations suggest that the hydrologic effect of Alternative Q+ is expected to be very similar to that of Alternative Q. Note that this difference plot does not capture sizable benefits already achieved through increment 1.2 using the Mod Waters and C-111 South Dade infrastructure. SOURCE: USACE, 2020b.

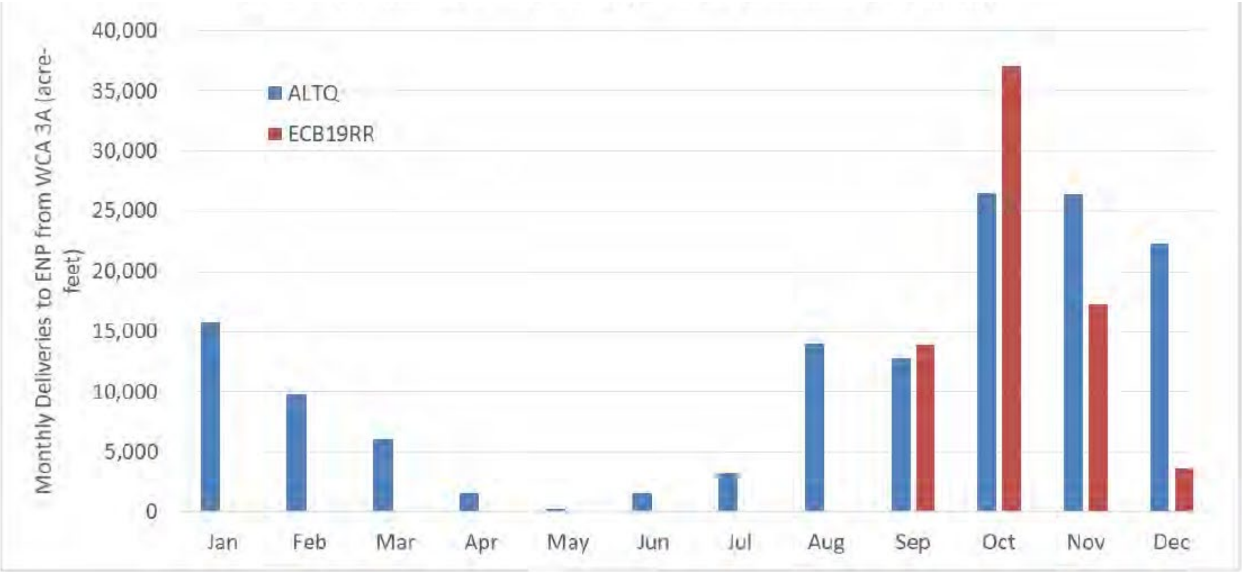

FIGURE 4-8 Monthly deliveries to Everglades National Park from WCA-3A under low-flow conditions (90% exceedance probability). SOURCE: USACE, 2020b.

Flows into the Eastern Panhandle of Everglades National Park and Taylor Slough will also increase under Alternative Q+. The increase is comparatively small for Taylor Slough, equaling 6,000 acre-feet per year on average, or 7 percent above the no-action alternative (ECB19RR), but is more substantial for the Eastern Panhandle, where annual inflows are forecast to increase by 30,000 acre-feet per year on average (or 27 percent) over the baseline. These additional flows are gained, in part, by reducing discharge through S-197, which has the beneficial effect of lowering excessive freshwater releases to Manatee Bay and Barnes Sound by 41,000 acre-feet per year (69 percent) compared to the no-action alternative.

Compared to the no-action alternative, Alternative Q+ is projected to increase freshwater flows into Florida Bay by 36,000 acre-feet per year, with the greatest increases in overland flow occurring through the Eastern Panhandle to the eastern basins of Florida Bay (see also Chapter 5). Nevertheless, seasonal deliveries of overland flow to the Florida Bay under Alternative Q+ will remain well below those typical of the natural system (see Chapter 5). Mod Waters and C-111 South Dade do not provide new storage; instead, the COP redistributes the existing water budget while remaining compatible with flow increases expected from future CERP projects.

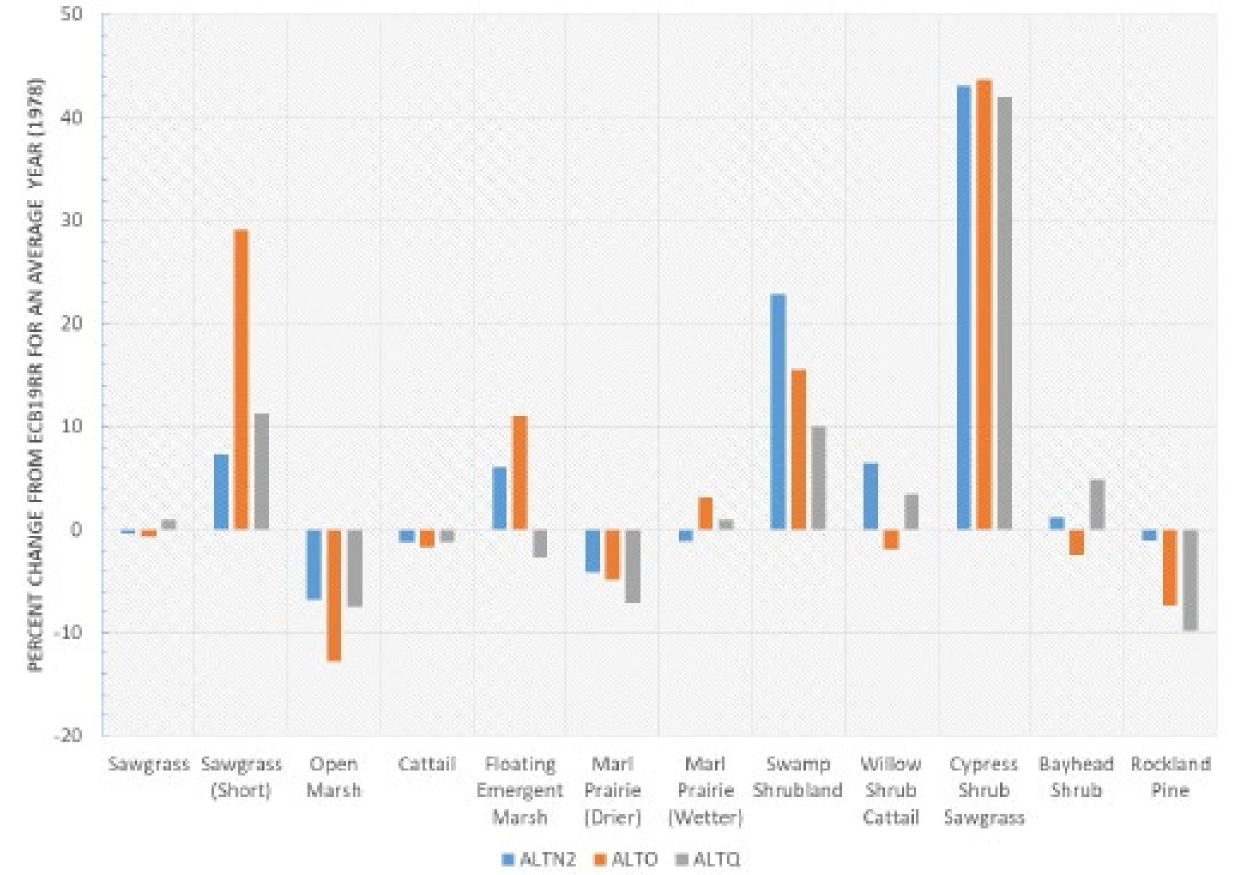

FIGURE 4-9 Percent change in acreage of vegetation predicted under the COP relative to baseline operations. Results are based on average precipitation conditions using the Everglades Landscape Vegetation Succession Model (ELVes) model. SOURCE: USACE, 2020b.

Benefits to Vegetative Communities

Hydrologic changes induced by implementation of the COP will promote ecological responses. Increases in hydroperiod within Northeast Shark River Slough and Taylor Slough are expected to reduce soil-oxidation rates, thereby promoting accretion of peat. Predictions made with the Everglades Landscape Vegetation Succession Model (ELVes) suggest that changes in the patterns and timing of inundation will lead to modest responses in the vegetative community. During an average rainfall year, for example, minor to moderate changes (< 10%) are predicted for the aerial extent of floating emergent marsh vegetation, cattails, and marl prairie vegetation relative to ECB19RR (Figure 4-9). Calculations of a slough-vegetation performance index[2] were made to assess the hydrologic suitability for slough communities under COP. Estimates of this performance measure are similar for the no-action and Alternative Q+ scenarios for areas west of the Miami Canal in northern WCA-3A, although Alternative Q+ scores slightly lower than the no-action alternative or Alternative O in the remaining portion of WCA-3A and WCA-3B. Within Everglades National Park, Alternative Q+ performed better for the index in Northeast Shark River Slough and southern Taylor Sough, but worse than Alternative N2 in central Shark River Slough. Tree island inundation is also reduced by the COP; the number of tree islands minimally inundated (for less than 10 percent of the period of record) is projected to increase by 24 percent for Alternative Q relative to ECB19RR, with the benefits concentrated in WCA-3 (USACE, 2020b).

Benefits to Endangered Birds

The COP aligns with the Reasonable and Prudent Alternative to ERTP to address the adverse effects of water management on endangered species articulated in the 2016 Jeopardy Opinion (FWS, 2016a). The USACE (2020b) concluded that the COP "may affect, but is not likely to adversely affect" most endangered and threatened species, including panthers, manatees, an endangered bat, alligators, and crocodiles, meaning that "all effects are beneficial, insignificant, or discountable."[3] This conclusion appears reasonable, and indeed the FWS accepted this conclusion in a concurrence letter issued in March 2019. The USACE entered into formal consultation with FWS on three species—wood storks, snail kites, and Cape Sable seaside sparrows—for which the Corps makes a "may affect" determination. These are the same three species that were the basis of the Jeopardy Opinion and that have been the source of conflicts between water management and endangered species management in the central Everglades since the mid-1990s. In this section, the committee assesses the impact of the COP on these species based on information provided in the COP Draft Environmental Impact Statement (USACE, 2020b) and supporting documents and discusses the ramifications for integrating restoration and endangered species conservation.

Wood Storks and Snail Kites

In their 2016 Jeopardy Opinion, the FWS concluded that ERTP did not jeopardize snail kites or wood storks, or destroy or adversely modify their critical habitat (FWS, 2016s). The COP is projected to benefit these species relative to ERTP; thus, there is little concern that protection of these species will pose any constraints in implementing the COP.

Wood storks. Simulations using the Wader Distribution Evaluation Modeling (WADEM) model indicate that the COP will result in improved foraging conditions for storks over large areas of northern and northeastern Everglades National Park (USACE, 2020b). The primary concern about storks is that the COP may result in excessive drying in northeastern WCA-3A in dry years, which would expose nesting colonies to high levels of nest predation and adversely affect foraging conditions, particularly in the area

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[2] The slough-vegetation performance measure was based on optimal hydrologic conditions to promote white water lily and bladderwort, which historically dominated Everglades sloughs under predrainage conditions.

[3] See https://www.fws.gov/midwest/endangered/section7/ba_guide.html.

of the Alligator Alley North supercolony. In the record nesting year of 2018, the number of wading bird nests in this colony exceeded the CERP goal for the entire Everglades ecosystem (USACE, 2020b) and accounted for 48 percent of all wading bird nests in the Everglades, making it the largest nesting colony observed since the 1930s (Cook and Baranski, 2019). The COP Adaptive Management Plan specifically addresses uncertainties in potential adverse impacts of the COP on the initiation and success of wading bird nesting and regional foraging conditions of this colony and in the project area generally (USACE, 2020b).

Snail kites. Snail kites are highly mobile and move throughout the Everglades ecosystem to find conditions favorable for foraging and nesting. Snail kites forage in nearly continuously flooded wetlands with relatively sparse emergent vegetation where they feed on apple snails and nest over water to reduce predation. In the mid-1990s, WCA-3A was their primary nesting area, but restrictions in flows to Western Shark River Slough to protect Cape Sable seaside sparrows resulted in water ponding in southern WCA-3A, exacerbating ongoing degradation of kite foraging habitat. As habitat conditions degraded, numbers of kites and kite nests declined and the distribution of nests shifted (NRC, 2012a). By the late 2000s, there was almost no nesting in WCA-3A, and the kite population had declined to one of the lowest levels ever recorded. Since the late 2000s, nesting has shifted to the Kissimmee Chain of Lakes, Lake Okeechobee, stormwater treatment areas, and other locations, and the kite population has rebounded (Fletcher et al., 2019) (Figure 4-10). Conditions for kites in the central Everglades continued to decline under the ERTP (FWS, 2016a), and kite nesting in the central Everglades, as a whole, remains minimal (Fletcher et al., 2019). The primary benefit to kites of the COP likely will be reduction of ponding of water in their former nesting area in southwestern WCA-3A. Otherwise, ecological modeling suggests that the COP will not significantly improve conditions for kites (USACE, 2020b).

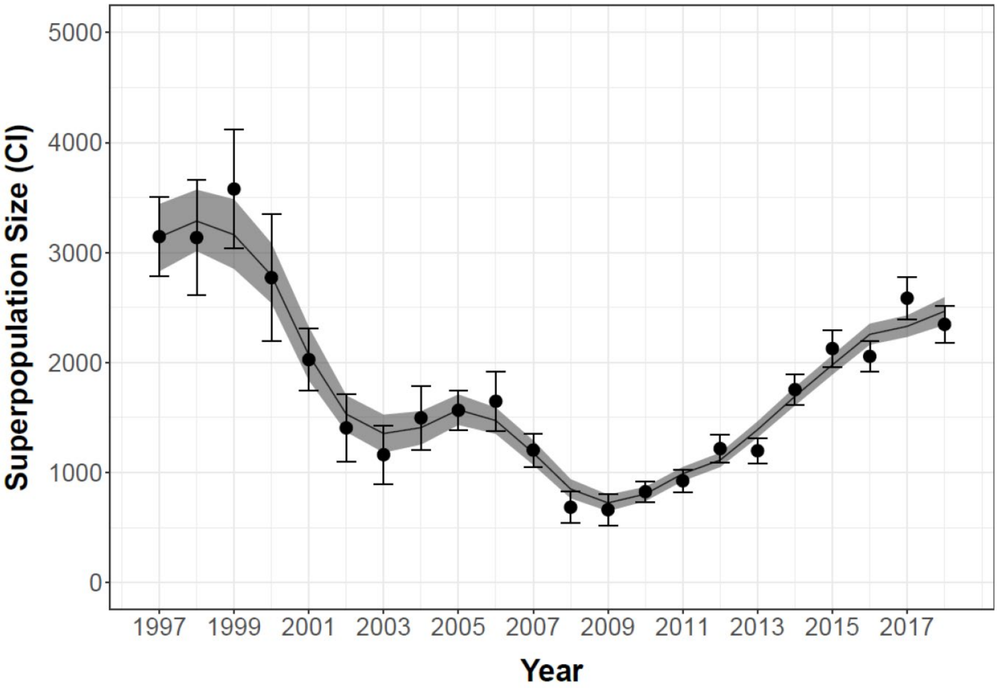

FIGURE 4-10 Population size of snail kites, 1997-2018. Black dots (and error bars) show population size estimates for each year (and 95% confidence intervals [CIs]). The black line shows the 3-year running average and gray shaded region shows the uncertainty around the 3-year running average (95% CI). SOURCE: Fletcher et al., 2019.

Based on the slight improvements in conditions for snail kites in the central Everglades, a major revival of kite nesting in WCA-3A or elsewhere in this region should not be expected. The return of hydrologic and ecological conditions that support kite foraging and nesting in the central Everglades may remain a kite recovery goal, but, thanks to the resiliency of this species, the survival of the snail kite is no longer jeopardized by failure to meet this goal. Unlike 20 years ago, kites now are doing well elsewhere in the Everglades ecosystem, where they feed on invasive as well as native apple snails and nest in a variety of locations. Hence, management of endangered snail kites does not pose a serious constraint on the COP.

Cape Sable Seaside Sparrows

In many respects, integrating restoration of the central Everglades with management of endangered Cape Sable seaside sparrows in the COP is a demonstration of the balancing among objectives that will be required for the full operation of the CERP. For the past 20 years, failure to protect the CSSS has forced water managers to alter operations designed to accomplish restoration. To prevent the COP from suffering the same fate as Experimental Water Deliveries and ERTP, it will be necessary to avoid exceedances established for incidental take for the CSSS. The poor current condition of the CSSS population, combined with impacts of the redistribution of water under the COP at the local scale, makes this very challenging.

The CSSS population, as of 2019, consists of one large (B), one medium (E), and four small (A, C, D, and F) subpopulations and an estimated total population of 2,688 birds (Figures 4-4 and 4-11). Subpopulations C, D, F, and, likely, A are even less productive than their small size suggests due to breakdowns in population dynamics and may be on the verge of functional extirpation (FWS, 2016a; Slater et al., 2014). The Reasonable and Prudent Alternative on which the COP is based calls for demonstration of progress toward several population goals including a trend toward positive population growth for 10 years, a total population size $\geq$ 6,600 for 5 years, a subpopulation A size of 2,100, and establishment of three self-sustaining, stable subpopulations (FWS, 2016a). It also includes a minimum total population size requirement of 2,281. It will be difficult to achieve progress toward the population goals and avoid violating this minimum population size requirement and thus triggering more consultation.

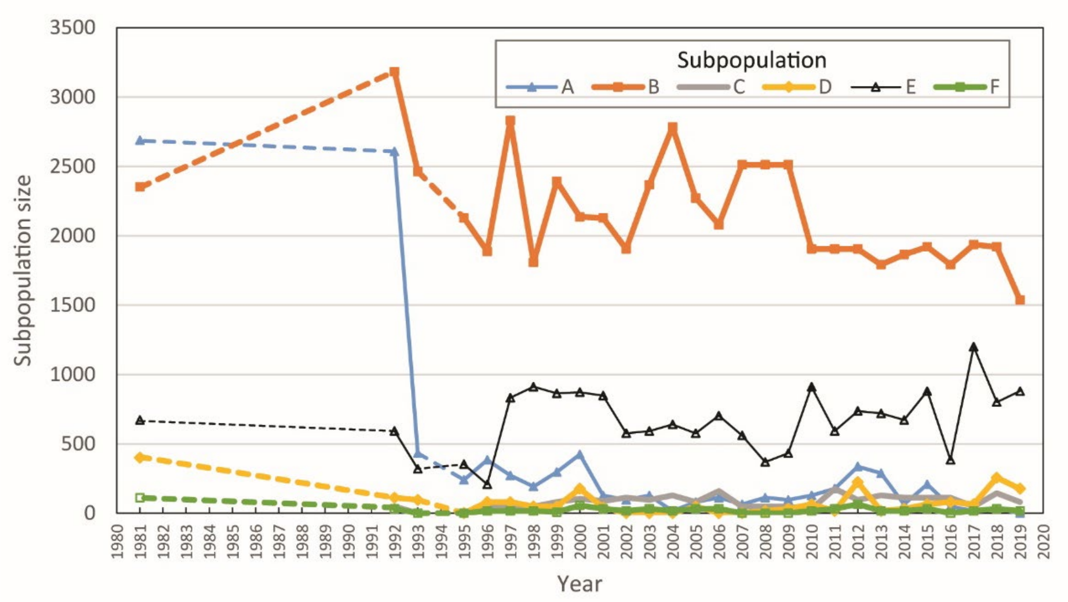

FIGURE 4-11 Changes in the size of CSSS subpopulations over time. Dashed lines indicate missing data. SOURCE: Based on data in FWS, 2020.

TABLE 4-2 Baseline and Alternative Q Performance Relative to the CSSS Criterion of 4-Year Running Average Hydroperiods Within the Range of 90-210 Days over 40 Percent of the Habitat Based on 1965-2005 Climate Data

	Average mean 4-year hydroperiod ± standardd deviation		Years that at least 40% of habitat met target for 4-year running average hydroperiod	
Subpopulation	**ECB19RR**	**ALT Q**	**ECB19RR**	**ALT Q**
A/Ax	242 ± 56	243 ± 57	7	8
B	146 ± 52	148 ± 52	35	34
C	102 ± 57	109 ± 55	19	21
D	188 ± 46	214 ± 50	28	12
E	204 ± 64	217 ± 65	22	17
F	136 ± 72	152 ± 75	24	23

NOTE: Green denotes average hydroperiod within the desired range of 90-210 days.
SOURCE: Data from USACE, 2020b.

TABLE 4-3 Baseline and Alternative Q Performance Relative to the CSSS Criterion of ≥ 90 Dry Nesting Days over 40 Percent of the Habitat Based on 1965-2005 Climate Data

	Average percent of habitat meeting >90 consecutive dry days		Years that at least 40% of habitat met target	
Subpopulation	**ECB19RR**	**ALT Q**	**ECB19RR**	**ALT Q**
A/Ax	46.2	44.2	20	18
B	76.6	75.5	37	35
C	83.9	87.3	36	36
D	53.2	46.0	24	21
E	57.7	50.0	27	23
F	70.8	69.1	30	30

SOURCE: Data from USACE, 2020b.

Based on modeling results using climate data from 1965-2005, USACE (2020b) presents information on the performance of the COP and its baseline in meeting hydrologic targets for sparrows in each of the subpopulations. Overall, the effects of the COP relative to the baseline are relatively small, with the exception of subpopulations D and E, which are getting much wetter under COP. The COP is projected to reduce the number of years that meet the hydroperiod target of 90-210 days in at least 40 percent of the habitat used by each subpopulation by 57 and 23 percent for subpopulations D and E, respectively. These areas also showed the largest reductions in the number of years that at least 90 dry nesting days occurred over 40 percent of the habitat (see Tables 4-2 and 4-3). Table 4-2 also shows that the overly wet hydrologic conditions for subpopulation A remain about the same under the COP.

Although modeling data are not available to compare COP to ERTP or pre-ERTP conditions, one can estimate the effects of implementation of the Mod Waters and C-111 South Dade infrastructure by comparing the COP modeled output for 1992-2005 to the observed conditions for the same period based on data of FWS (2016a). Issues such as model bias make comparisons of modeling results to real data challenging, and these comparisons assume the model errors for the comparison period are small relative to the size of the effects. Nevertheless, these comparisons provide an approximation of how hydrology will differ from previous conditions under COP. Figures 4-12 shows that improvements in hydroperiods primarily are due not to Alternative Q+ but to operational changes made though Increment 1.2 (the COP baseline, ECB19RR), particularly for subpopulations B and F, which were overly dry areas. A small hydroperiod benefit, as well as an increase in the occurrence of > 90 dry nesting days over 40 percent of the habitat, attributable to the Increment 1.2 baseline is observed for the problematic, overly wet subpopulation A (Figure 4-13). These comparisons reinforce modeling results indicating that some subpopulations (D, E) may fare worse under Alternative Q+ and further suggest that habitat conditions, particularly for nesting, might be little improved or even poorer under COP than under pre-CERP water management (Figure 4-13).

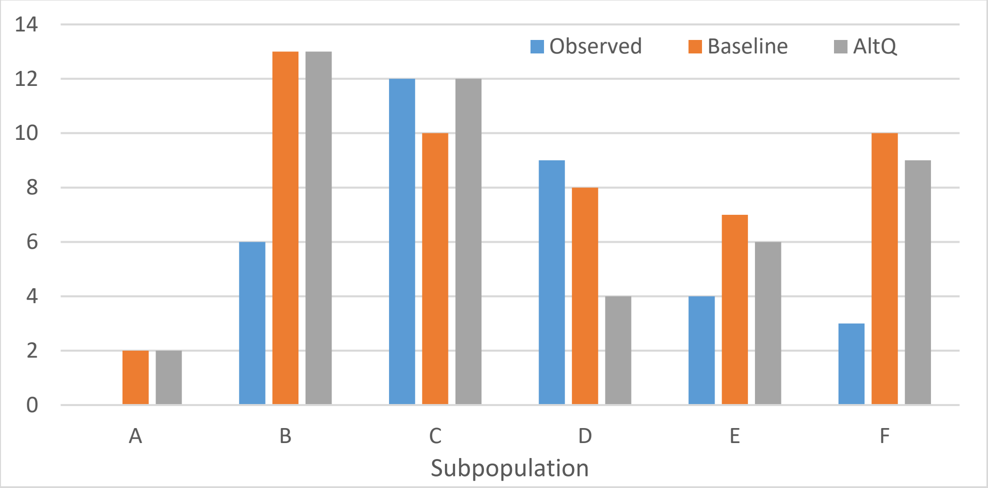

FIGURE 4-12 Number of years between 1992 and 2005 in which the criterion of a 4-year running average hydroperiod of 90-210 days over 40 percent of the habitat for each CSSS subpopulation was observed (blue bars) or was projected to occur under ECCB19RR baseline conditions (orange bars) or COP Alternative Q (gray bars). The difference between the orange and blue bars can be used to estimate the benefits provided by the Increment 1.2 baseline operations relative to the water management applied in 1992-2005, assuming small model errors during that period. SOURCE: Data from COP EIS and FWS (2016a).

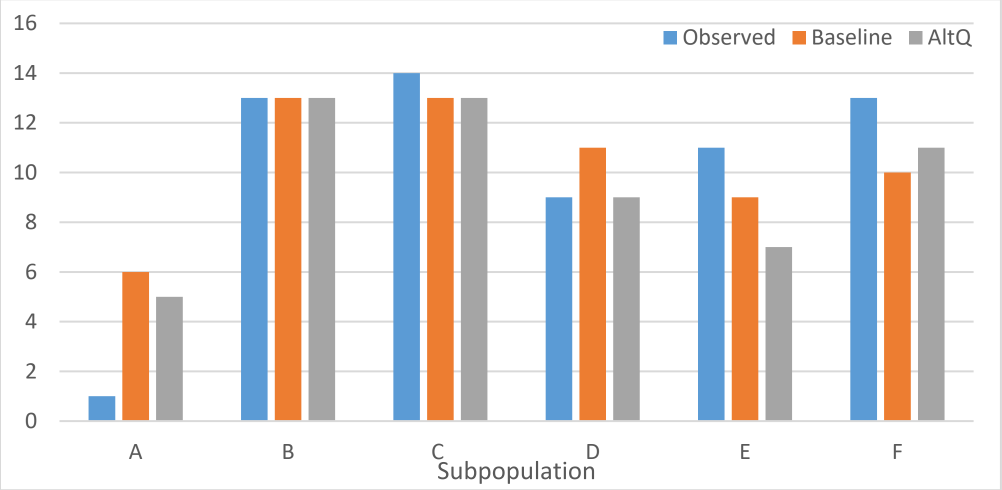

FIGURE 4-13 Number of years between 1992 and 2005 in which the criterion of ≥ 90 dry nesting days over 40 percent of the habitat was observed (blue bars) for each CSSS subpopulation or was projected to occur under ECCB19RR baseline conditions (orange bars) or COP Alternative Q (gray bars). The difference between the orange and blue bars can be used to estimate the benefits provided by the Increment 1.2 baseline operations relative to the water management applied in 1992-2005, assuming small model errors during that period. SOURCE: Data from COP EIS and FWS (2016a).

These and other results presented in USACE (2020b) suggest that restoring the historic distribution of flow between Western and Northeast Shark Slough, although beneficial to sparrows at a large scale, will not necessarily resolve the issues that have led to multiple jeopardy opinions over the last 20 years. Although the COP will improve conditions for subpopulation A, conditions will remain too wet in most years relative to target conditions for nesting (Figure 4-13). Increased flows to Northeast Shark Slough and Taylor Slough will produce a complex mix of improvements in some areas and adverse effects in others. This is not a surprise, as it mirrors results of modeling associated with the CEPP (FWS,

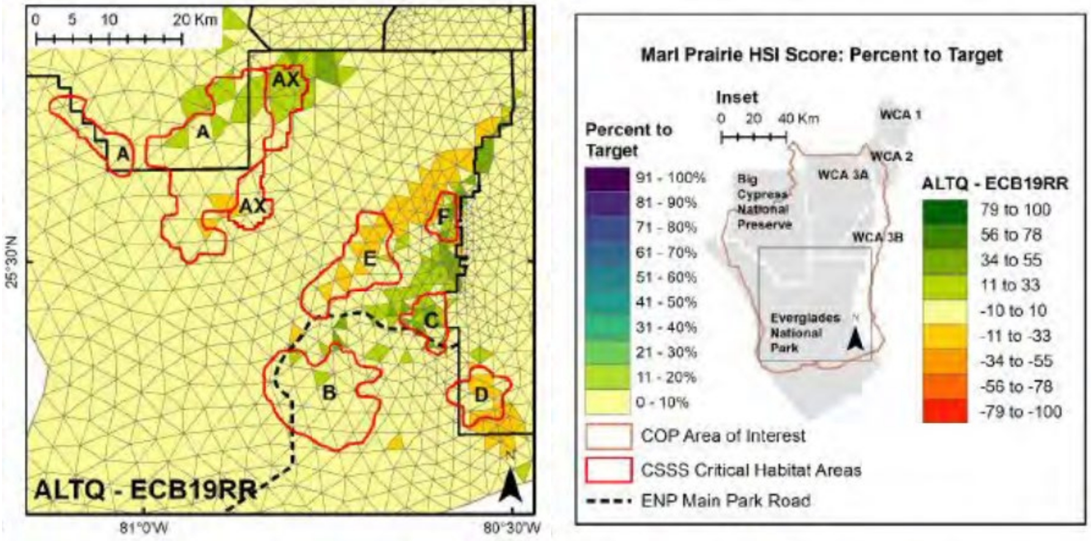

FIGURE 4-14 Difference in marl prairie habitat suitability between Alternative Q and the baseline conditions. SOURCE: USACE, 2020b.

2014; USACE and SFWMD, 2014) previously reviewed by the committee (NASEM, 2016). Restoration of the central Everglades will create new CSSS habitat in some locations, and convert currently suitable marl prairie to wetter habitat types in others. Specifically for the COP, adverse effects are expected close to sloughs, and benefits farther away from sloughs (Figure 4-14). New habitat for subpopulation A will be created in the northern part of the area (Ax) known as the expansion area, which is already occupied by some sparrows. Modeling also indicates there will be a considerable area of suitable, currently unoccupied habitat between subpopulations B, C, and F, and a smaller amount northeast of F. Of concern are projected reductions in habitat for subpopulations D and E (the second largest) (Figure 4-14).

The COP Biological Opinion. In the Biological Opinion on the COP, which was released in May 2020, FWS (2020) concluded that the COP will not jeopardize the continued existence of CSSS, snail kites, or wood storks or adversely modify their designated critical habitat, and noted that USACE will achieve all the actions and timelines of the Reasonable and Prudent Alternative described in the ERTP Jeopardy Opinion with the implementation of COP. FWS defines incidental take, and criteria for exceedance of authorized take that could trigger reinitiation of consultation, for all three species. The analyses and conclusions presented in the Biological Opinion are similar to the committee's independent assessment in most respects. However, FWS (2020) appears much more optimistic than the committee that the CSSS is unlikely to constrain the COP.

FWS relied on the same analyses in USACE (2020b) and performed the identical comparisons of observations to model projections (Figures 4-12 and 4-13) as the committee. They reached the same conclusions about much of the benefit from Mod Waters and C-111 South Dade to sparrows being captured in the ECB19RR baseline and modest benefits for the problematic subpopulation A. FWS (2020) noted the adverse effects on subpopulations D and E, reduced performance of Alternative Q+ compared to the baseline for these three subpopulations, and projected creation of new sparrow habitat. However, FWS (2020) does not foresee the need for mitigation to redistribute sparrows on the landscape for the COP to remain in compliance with the Endangered Species Act with respect to Cape Sable seaside sparrows. The estimated sparrow population in 2019 was 2,688 birds, based on 168 birds detected.[4] The new incidental take exceedance criterion in FWS (2020) is a population size estimated from annual surveys of at least 2,387 birds. If 19 fewer birds are detected in a subsequent survey, authorized incidental take will be exceeded; the number of birds detected has differed from the previous survey by more than

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[4] The methodology for CSSS population assessments uses a multiplier of 16 for every bird counted in the field.

19 birds in 7 of the past 9 years. Furthermore, in subpopulation A, which FWS views as critical to the continued existence of the sparrow (FWS, 2020), no birds were detected in 2019.

Active mitigation strategies. Given the precarious state of the CSSS and the projected impacts of COP on subpopulations A, D, and E, the next water management crisis over the sparrow is likely to be triggered by adverse effects from the COP on existing sparrow habitat. One can imagine demands to constrain flows to Northeast Shark River Slough and Taylor Slough to protect the sparrow, impacting broader ecological restoration goals for the region. Active mitigation for sparrows is the key to integrating Everglades restoration goals with CSSS recovery. To offset adverse effects expected on some sparrow habitat, sparrows will need to be redistributed on the landscape, such that new subpopulations in new habitat more than compensate for any losses of sparrows in current habitat. This may require active measures such as translocation of sparrows to new habitat, rather than relying on the birds to colonize new areas. If the COP is to avoid the fate of previous water management plans, it would behoove managers to design and begin executing plans to establish sparrows in newly created habitat now rather than waiting for a crisis to force them to do so.

The COP provides the first opportunity to implement active mitigation strategies and, based on their results, develop a systemwide sparrow conservation plan for CERP. Thus, as with many other aspects of restoration, the COP provides an opportunity for adaptive management of CSSS recovery that has programmatic applications. Hopefully, it marks the beginning of the resolution of the constraints the CSSS has posed for water management, and the restoration.

Committee Evaluation of the Process

The process used to identify, evaluate, and select a preferred alternative for the COP was systematic and comprehensive. The evaluation used information from both field testing and modeling, with modeling playing a particularly central role in evaluation of final alternatives and development of the flow formula used to implement the final preferred alternative. The planning process also incorporated significant stakeholder input, which, although widely promoted, may nudge evaluation toward objectives that differ from the stated objectives (Layzer, 2008). Although there is much to praise in the COP formulation, evaluation, and selection process, future CERP operational evaluation would be improved by explicit consideration of uncertainty, transparency in the consideration of stated objectives, and evaluation of performance under future conditions. The following comments address points where the process could more fully follow best practice and be a true exemplar for future CERP project development.

Consideration of Model Uncertainty

The best practice approach in modeling is to characterize the uncertainty of the models being used (Lehrter and Cebrian, 2010; Rinderknecht et al., 2012; Ruppert et al., 2012). By doing so, one can produce a more realistic range of what the observed results are likely to be, given the uncertainty of the model. The implementation of the COP is enabled by the TTFF, a multiple linear regression model. The regression was created using the water releases from the iModel (Ali, 2015) and RSM-GL, which provide optimal releases for a specified objective function as the target. Linear regression has been used previously in water resources management for deriving reservoir operational rules from the results of optimization models (Lund and Ferreira, 1996). Using this technique for guiding operations requires an understanding of how different from the expected flow value the actual flow value might be when the operational rules are applied. For example, given particular values of previous flow, precipitation, potential evapotranspiration, and storage levels in the WCAs in a given time step, the TTFF produces a specified flow release target for S-12C, S-12D, and S-333. Decision makers need to know how well those release targets are likely to match the optimized targets and, consequently, how likely the releases are to meet the objectives that are sought (and expected). This is relevant for the COP but also relevant to the CERP more generally. To answer these questions, planners need to understand how likely it is that actual observed results of projects will be similar to the model-estimated results and how much error is tolerable without significant implications for achieving objectives. Since model-estimated results are often a primary input to project design, the answer to these questions has significant consequences for the success of CERP.

For example, in the case of the TTFF, a regression model produces a conditional mean estimate of the target flow release, which is used for operations, and also specifies the full uncertainty distribution for the flow (i.e., the range of the flow values that the iModel could have produced for the current state of the state variables). The uncertainty analysis (see Appendix H, Annex 8 of USACE [2020b]) presents figures related to the errors of the regression, showing no reason to reject the model. This is good modeling practice and an example for model evaluation in all CERP projects. No such evaluation of error and range of uncertainty is provided for the RSM-GL, however, which was used for selecting the preferred alternative. In both cases, what this range of uncertainty implies for the selection of the COP alternative is unclear. This range of uncertainty in the TTFF may be within the range of difference in outcomes between the alternative plans. The possible range of outcomes for the performance metrics is also unknown. Selections among COP alternatives were made based on differences in the model results, but it is unclear if the differences between alternatives were meaningfully significant relative to the model uncertainty. Despite the challenges in quantifying the implications of scientific uncertainty on restoration decisions (e.g., Estenoz and Bush, 2015), the presentation of uncertainty, such as the range of expected outcomes, helps to set more reasonable expectations. It also is essential for adaptive management, because when monitoring reveals observed performance metrics, one must know whether they fall within the range of expectations (which corresponds to the range of model uncertainty) or whether they are truly anomalous and indicative of a problem (see also Chapter 6).

Transparency of Multiobjective Trade-off Analysis

The process for selecting the preferred COP alternative was a systematic evaluation of alternatives using a set of performance metrics representing the multiple objectives for this project. Multiple performance metrics were considered, including both ecological performance and effects on flood risk, as well as considerations related to water quality and water supply. However, even though the objectives for COP were strictly ecological, it is not clear that the selected Alternative Q+ provides the most ecological benefit, particularly in comparison to Alternative O, and what role other factors, labeled planning considerations and concerns, played in project evaluation. Meeting previously defined levels of flood risk management was a mandated constraint on the COP, yet the planning consideration of enhancing flood mitigation also emerged as an important factor in alternative evaluation. If enhanced flood mitigation was provided at the expense of meeting ecological benefits, best practice would require that this was clearly laid out. Any differential weighting of planning considerations, like enhancing flood mitigation, also needs to be documented. Transparency on the trade-offs between objectives, and between objectives and planning considerations, would enable a clearer understanding of the selection process and the extent that ecological targets were compromised due to other considerations. Perhaps there is a very limited trade-off and objectives move in concert. Through the use of trade-off curves, including parallel coordinates plots (Wegman, 1990), the process for selecting the final alternative can be made more transparent, providing better understanding for concerned stakeholders regarding why decisions were made as they were.

Evaluation of Performance under Future Conditions

Finally, an inherent challenge for the CERP generally, and applicable to the COP, is how to evaluate the performance of an alternative in the future world in which it will be operating. The expected performance of the COP preferred alternative is entirely based on historical conditions, and the implementation formula is a regression based on historical climate conditions. However, future precipitation and temperature will surely vary from what has occurred historically, due to both the inherent variability of the climate system as well as climate change. Boundary conditions related to sea level in Florida Bay also will likely influence the performance of the COP at the southern boundary. Given these kinds of uncertainties, best practices would seek to evaluate alternative designs based on their ability to provide an acceptable level of performance over a wider range of possible future conditions, rather than focusing on the alternative that performs best over a single historical period. This could have been performed as part of the COP evaluation, for example, by using, at a minimum, stochastic time series of precipitation and temperature inputs that provide a wider range of likely climatic conditions than exhibited in the historical record. In terms of climate change, scenarios of moderate warming might be more indicative of performance of the COP than the historical record. This is important not only for COP alternative selection, but also for providing a more realistic set of expectations for the results of the COP and the CERP more generally.

COP ADAPTIVE MANAGEMENT

The COP provides a tremendous opportunity for learning with respect to restoring the central Everglades, with valuable lessons for the CEPP. As water is redistributed in the central Everglades under the COP, projected changes in hydrology can be compared to observed changes, and projected responses of the ecology can be compared to observed responses. Differences outside of the range of model uncertainty can be identified and used to improve understanding of how the system will respond to restoration as well as the models employed. What will be learned will inform COP operations, enabling adjustments through adaptive management to meet project objectives. In addition, much of this learning will have systemwide applications, informing projections of the impact of future projects such as the CEPP, enabling adaptive adjustment in the design of those individual projects and perhaps the CERP itself. For these reasons, adaptive management in the COP has more potential than any other Everglades restoration project that has been implemented.

The committee commends the COP project development team for seizing on these opportunities for learning. Adaptive management was a component of the development of the COP, as learning from the incremental field tests informed the design of the COP. A detailed Adaptive Management and Monitoring Plan for the COP provides a framework for learning to continue to inform COP operations and the design of future projects. In this section, the committee reviews the Adaptive Management and Monitoring Plan and the opportunities for learning and adaptive management as well as demonstrating restoration success that the COP presents.

The COP Adaptive Management and Monitoring Plan

The COP Adaptive Management and Monitoring Plan (USACE, 2020b, Appendix C) is quite comprehensive and is comprised of several parts, including monitoring plans and a component labeled COP Adaptive Management that focuses on COP operations. Even though the COP is a non-CERP effort, the adaptive management component follows the blueprint established for CERP adaptive management (USACE and SFWMD, 2011b) with strategies developed in RECOVER (2015). Key steps include identifying uncertainties, developing matrices of management options, assessment, feedback to decision makers, and adjustments in management.

Identifying Uncertainties and Management Options

The team first identified and prioritized uncertainties that might limit meeting COP goals. Which uncertainties to include in the plan was determined during a workshop held in July 2019 using a ranking and prioritization scheme. Uncertainties were screened based on a set of criteria including relevance to COP goals, spatial scale, ability to be addressed through COP adjustments, and existence of measurable attributes that can resolve the uncertainty. Uncertainties were then ranked by the workshop attendees based on three factors: risk (i.e., ability to meet COP goals if not addressed), level of current knowledge, and relevance to COP adaptive management. This process resulted in 10 ecological uncertainties, 6

BOX 4-3 Uncertainties of the COP Adaptive Management Component

Ecology

- **Flows, salinity, and peat collapse:** Will predicted COP flows mitigate saltwater intrusion and associated coastal wetland vegetation, soil stability, and nutrient retention or release? How do changes in salinity influence nutrient availability and what are the ecological consequences?
- **Tree islands:** Can COP create favorable hydrologic conditions to sustain individual islands and increase soil elevation on tree islands?
- **WCA-3B vegetation:** Are COP operations likely to decrease hydroperiods and water depths in WCA-3B and cause the expansion of sawgrass in the remnant ridge and slough area?
- **S-197/Manatee Bay discharges:** How can the quantity, timing, distribution, duration, and quality of discharges into Manatee Bay and overland flow into northeast Florida Bay be managed to promote restoration, sustain seagrass habitat, and avoid harmful algal blooms?
- **Hydrologic transmissivity:** Can vegetation management south of Tamiami Trail be used to increase flow and manage flow direction from the Tamiami Trail Canal?
- **Pennsuco wetlands:** Will COP reduce surface- and/or groundwater base flows and wetland/groundwater recharge to the east of the L-30 in areas such as the Pennsuco Wetlands?
- **Soil oxidation and peat fires:** Are inundation and hydroperiod sufficient to reduce current high rates of soil oxidation and peat fires?
- **Wading birds in Alligator Alley North Colony:** Will changes in hydrology under the COP negatively influence the Alligator Alley North Colony in WCA-3A?
- **Whitewater Bay, Florida Bay, and southwest coast estuaries:** What are the water quality impacts and ecological benefits of changing patterns of freshwater flow into estuarine waters of the southern Everglades?
- **Wading birds:** How much will hydrologic restoration result in potential changes in wading bird foraging conditions and nesting under the COP?

Hydrology

- **Seepage/flood protection:** Do COP operations, while leveraging existing seepage management infrastructure, sufficiently support project objectives and constraints?
- **Northeast Shark River Slough and Taylor Slough:** Will increased flows to northeastern Shark River Slough and toward the southeastern Everglades (Taylor Slough and lower C-111 basin) yield natural distribution of waters and moderate recession rates? Are flows toward Taylor Slough sufficient to alter the anticipated flows or stages (recession rates)?
- **Tamiami Trail Flow Formula General:** Based on consideration of the existing water budget used to formulate the COP, is there an opportunity to improve the Tamiami Trail Flow Formula such that desired ecological targets are more universally achieved?
- **Tamiami Trail Flow Formula and drought:** Based on consideration of the upstream water availability is there an opportunity to deliver water to Northeast Shark River Slough in a specific manner such that the delivery enhances freshwater flows to Florida Bay by delivering more water during the dry season without harming the ecological condition of WCA-3?
- **Florida Department of Transportation constraint on Tamiami Trail:** Can L-29 Canal elevations be raised to 8.5 feet NGVD for more than 90 days per water year without adversely impacting the safety and stability of the Tamiami Trail roadway between S-333 and S-334? Following completion of the roadway reconstruction under the Department of the Interior Tamiami Trail Next Steps project, to what extent, if any, does the 8.5 square-mile area flood mitigation requirement limit the ability to operate the L-29 Canal up to 8.5 feet NGVD beyond the 90-day restriction assumed in place through at least the 2020 wet season?
- **Saltwater intrusion:** What are the effects of sea-level rise on COP operations, resulting salinity patterns in Florida Bay, water supply risks associated with saltwater intrusion, and ability to meet flood protection constraints?

Water Quality

- **Water quality in Taylor Slough:** Will there be downstream biogeochemical effects associated with modifying inflows and hydrologic conditions in ENP that result in detrimental effects on nutrient movement, availability, and ecological responses?
- **Water quality in Northeast Shark River Slough:** Will there be downstream biogeochemical effects associated with modifying inflows and hydrologic conditions in ENP that result in detrimental effects on nutrient movement, availability, and ecological responses?

hydrologic uncertainties, and 2 uncertainties related to water quality that were included in the COP Adaptive Management component (Box 4-3).

The team then constructed Management Options Matrices for the 18 selected uncertainties that contain options of how to improve restoration performance if goals are not being met. The Management Options Matrices link monitoring, thresholds that indicate deviations from expected performance, and management actions to address undesirable deviations in hypothesis testing frameworks. These matrices are an adaptive management blueprint for addressing each uncertainty. They are intended to inform decision makers, agencies, and the public on the potential actions that can be taken adaptively to improve COP performance, if monitoring shows that the expected performance has not been met or that more benefits can be achieved within the project constraints. Box 4-4 outlines one example.

The uncertainties identified in the COP Adaptive Management component all are important, and the monitoring associated with them tracks critical information that provides opportunities to learn about responses to restoration efforts. The focus of management responses is on the mechanics of COP operations, particularly for hydrologic uncertainties. However, most will provide information that has implications well beyond its application to COP operations. For example, the monitoring for the tree island uncertainty (see Box 4-4) will provide much more than a linkage between an ecological response and a specific set of water structure operations. Additional value lies in new understanding of the underlying physical or biological processes that links the action to the outcome, which requires a determination of the reason the expected outcome was not achieved. In addition to a correctable problem in operations, possible reasons an expected outcome may not be achieved include inaccuracies in hydrologic or ecological model predictions, errors or gaps in conceptual models of ecosystem dynamics

BOX 4-4 Example Management Options Matrix for Tree Island Uncertainty

One uncertainty addresses whether COP will create favorable hydrologic conditions to sustain individual islands and increase soil elevation on tree islands. The predictions are that, under the COP, vegetation density on tree islands will increase, edges of tree islands will sharpen, and structural complexity of tree islands will increase. The first trigger, like the majority of those included in the Management Options Matrices, is based on these predictions proving false (Table 4-4). The second trigger relates to a performance measure that traces back to the ERTP biological opinion (FWS, 2016a). Modeling of this performance measure was included in the development of the COP, and thus projections of expected performance of this measure exist. Four potential changes in management are linked to these triggers.

TABLE 4-4 Management Options Matrix for Uncertainty #8: Tree Islands

Specific Property to be Measured	Trigger(s) for Management Action	Management Action Options Suggestions
• Tree island boundaries and area • Maximum tree/island height • Functional vegetation composition • Locations of additional new or missing tree islands (Mapping every 2-3 years)	• Change in tree island number, size, and boundary firmness that indicates ecological degradation of tree islands is occurring and where • Occurrence of more than 60 days of inundation of high-elevation tree islands in 2 consecutive years or 120 days of inundation in any single year Specific thresholds for vegetation change will be developed as part of the CEPP effort	• Create moat-like sloughs around tree islands using vegetation management options (e.g., fire, harvesting, herbicide, physical stress) • Increase operational flexibility to maximize flow velocities in the key areas including (1) hydrologic pulsing and (2) vegetation clearing or management • Incremental increases to WCA-3B hydroperiods to create more resilient tree islands with higher elevations in anticipation of a future increment of CERP • Adjust operations along the northern boundary of WCA-3A by redistributing water into the S-8

NOTE: Indicator, time frame, region, and cost columns from the original table are not included.
SOURCE: Adapted from USACE, 2020b.

(e.g., Davis et al., 2005), or limits in our understanding of ecosystem responses to restored hydrology (see also Chapter 6). Indeed, the COP adaptive management plan provides opportunities to test the long-held belief that "getting the water right" will result in ecological restoration.

There are obvious systemwide implications of the hypotheses testing for most of the COP uncertainties, provided the cause of deviations from expectations can be determined. For example, flood mitigation for the 8.5 square-mile area and seepage issues on the eastern boundary of Everglades National Park have implications not only for COP benefits, but also for restoration of the central Everglades moving forward. Currently Tamiami Trail roadway protection and flood mitigation for the 8.5 square-mile area are constraints limiting the number of days the L-29 Canal can be operated at a stage > 8.3 feet NGVD, even though the infrastructure was designed to support levels up to 8.5 feet, although Tamiami Trail Next Steps will address the roadway protection issues. If the current plan is limited by seepage and flood control, CEPP too, which envisions L-29 Canal levels up to 9.7 feet NGVD, will be impacted unless additional seepage management or flood control strategies are developed. One of the uncertainties in the COP Adaptive Management Component addresses this seepage constraint, and knowledge gained could inform future seepage control planning, including a study of additional seepage barriers being conducted in 2020 by the SFWMD.[5]

The COP Adaptive Management component identifies the monitoring needed to address the uncertainties. The monitoring plan in support of adaptive management is largely based on current monitoring and thus adds little additional monitoring costs. Appropriately, as a precursor to the CEPP, it relies heavily on critical monitoring identified in the CEPP, although the plan also identifies other ecological, hydrologic, water quality, and cultural resources monitoring that could be used to address uncertainties. Thus, the COP provides an unprecedented opportunity to demonstrate, as well as assess, restoration success in the central Everglades. USACE (2020b) generally concludes, especially regarding ecological indicators, that the current monitoring programs are adequate to address the questions posed in the COP Adaptive Management component, but the report is vague with regard to how the utility of the monitoring programs was evaluated. Many of the current ecological monitoring programs were developed for evaluating either status or trends. Many of the decisions will involve models, either statistical or complex coupled hydrologic/ecological models. Monitoring designed for evaluating status or trends may be inadequate for goals of these models, which is often prediction or a focus on a subregion of the model spatial extent. The monitoring plans should be evaluated to determine whether additional monitoring that is better connected to COP adaptive management decisions and targets is needed to augment the current monitoring. For example, several monitoring programs are based on a stratified random sampling scheme (Evans et al., 2019; Philippi, 2007). Such monitoring is useful for balancing sampling across different types of heterogeneous units (e.g., different habitat types) and is best for estimation of an overall mean or total, with low variance. However, stratified sampling may not be the best design for different problems of interest (EPA, 2002; Hirzel and Guisan, 2002) such as regression modeling. Other approaches may better support adaptive management or aid decision making based on computer or statistical models (Conroy et al., 2011; Lindenmayer et al., 2011; Nychka and Saltzman, 1998; Yakirevich et al., 2013).

Assessment, Feedback to Decision Making, and Making Adjustments to Management

The final steps in the CERP adaptive management framework are assessment, feedback to decision making, and adjustment. These are the means by which monitoring outcomes result in changes in management. How these steps will be accomplished is described in some detail for the COP Adaptive Management component.

Feedback to decision making and making adjustments to management. The management changes linked to the 18 uncertainties are classified into three categories depending on whether additional NEPA permitting/review will be required to implement them:

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[5] See https://www.sfwmd.gov/our-work/south-dade-projects.

A. Adaptive management options defined in the COP water control plan and supported by the environmental impact statement (USACE, 2020b),
B. Adaptive management options not defined in the COP water control plan and not supported by the environmental impact statement (USACE, 2020b), and
C. Adaptive management options not in COP authority.

Only 8 percent of the management options are in category A, and these address two uncertainties—Northeast Shark Slough water quality and the TTFF. The remaining management options may require additional NEPA permitting and review, which typically is a time-consuming hurdle. However, 76 percent of the management options presented fall in category B, for which additional NEPA review is "dependent on the degree of proposed change to water management criteria."

Several mechanisms for feedback to decision making are outlined in the COP Adaptive Management component. These include

- Weekly operations meetings involving SFWMD operations managers,
- Periodic science calls among scientists from the agencies and stakeholders involved in COP to discuss monitoring results and forecasts (held every 3 to 4 weeks),
- Wildlife coordination calls involving personnel from various agencies with interests in wildlife (held on a weekly to monthly basis), and
- Meetings of the COP Project Delivery Team (known as COP-PDT+), successor to the Project Development Team, composed of representatives from the COP implementing agencies, oversight agencies, and stakeholder groups (held at least once per year, but likely more frequently in the first few years of implementation).

Communication between these mechanisms is also envisioned. Wildlife coordination calls can provide recommendations to operations managers and periodic science calls, and periodic science calls can provide recommendations to operations managers.

Although operations managers typically have the authority to make adjustments to operations within the flexibility existing within the Water Control Plan based on these inputs and their own deliberations, none of the management options contained in the COP Adaptive Management component fall within the decision-making authority of operations managers. Decisions about management options in categories A and B will be made by "senior agency officials" (USACE, 2020b). Recommendations from the periodic science calls and the COP-PDT+ are envisioned as mechanisms for providing feedback to these decision-makers. Recommendations from the COP-PDT+ is the only mechanism for feedback to inform decision making for adaptive management adjustments beyond the scope of the COP (category C), involving changes to the CERP generally or projects such as CEPP specifically. The decision-making authority for such programmatic-level adaptive management is not specified.

Assessment. In contrast to other parts of COP Adaptive Management, mechanisms for assessment are not well specified. Assessment represents the most vulnerable part of the adaptive management plan as one can imagine several ways in which deficiencies in assessment could limit effective implementation of adaptive management. Assessment requires rigorous design of monitoring programs and analysis of monitoring data by skilled staff and the application of modeling tools to maximize learning, given natural variability (see also Chapter 6). For example, there is a need to distinguish between the normal range of performance of the TTFF (based on the model) and observations falling outside that range that suggest the TTFF requires adjustment. Some of this may be envisioned as part of the routine functions in support of the periodic science calls and the COP-PDT+. The COP-PDT+ will also receive assessment input in the form of a biennial report that describes COP operations and monitoring. All of this assessment, whether it involves writing the reports, analyzing the monitoring data, or presenting findings to the periodic scientist calls and the COP-PDT, will fall to core agency staff assigned to COP adaptive management duties. This is a large body of work, and the quality of assessment and thereby the success of the COP Adaptive Management plan, will depend on investment in staffing (see also Chapter 6).

Overall Assessment

There is much to commend about the COP Adaptive Management component. The right questions are being asked, monitoring has been identified to address these questions, and results are linked a priori to triggers for consideration of potential changes in management. The plan provides the means to demonstrate restoration success and unprecedented opportunities to manage adaptively at the project scale and beyond. However, whether the plan is successful will depend on the adequacy of existing monitoring plans to address the specific decisions and the level of investment in assessment, which is unspecified. Success in managing adaptively will also depend on the decision-making process, which also is unspecified beyond being the responsibility of senior agency officials.

Resources and experienced scientific staff will be needed to support the COP-PDT+ to provide routine multiagency review of the monitoring and assessment results and develop recommendations for management (e.g., changing operations, undertaking additional NEPA analysis). Skilled staff will also be needed to help communicate this information effectively and develop programmatic linkages between the COP-PDT+ and CEPP managers to share decision-relevant information. As the restoration of the Everglades pivots from project planning to project implementation, the role of science becomes increasingly important to accomplish the two tasks that will dominate this phase of the restoration: evaluation of restoration success and adjustments of operations and management in response (see also Chapter 6). This phase begins in earnest with the COP.

Other Opportunities for Learning

Overall, the COP Adaptive Management component focuses on project-level learning and adaptive management, but there are additional opportunities for systemwide applications of learning and programmatic adaptive management. Specifically, additional activities to compare modeling predictions to observed system behavior could be applied that would improve systemwide understanding and modeling tools, thereby benefiting both the COP and the CERP as a whole.

Differences between predictions and observations might reveal correctable failures in operations in some cases, but in others they might reveal deficiencies in the models used to make those predictions or deficiencies in understanding of the system that have systemwide applications. As with the Decomp Physical Model, water may not flow in the direction expected, revealing a deficiency in understanding of hydrology (NASEM, 2016). An ecological component may not respond to restored hydrology as expected; that is, getting the water right might not result in ecological restoration. An action taken to produce benefits for one component of the system may have unanticipated consequences for others. Interpreting deviations between outcomes and expectations in a context broader than COP operations is critical to taking full advantage of the learning opportunities provided by the COP. This task requires being able to compare observation to model projections for the same years. Thus, modeling of current conditions is needed, but modeling for the COP, to date, is based on the historical record (1965-2005). Modeling of current conditions, including recent years prior to the COP incremental field tests, could be used to demonstrate and communicate fully the benefits of the Mod Waters and C-111 South Dade infrastructure investments (see also Chapter 6). There is a great opportunity to link new knowledge gained through the various monitoring activities to continuously improve the modeling/predictive tools. However, there is little mention in the COP Adaptive Management component of plans to incorporate new knowledge (and data) into modeling tools to reduce uncertainties and improve their predictive abilities. There is some discussion of the high degree of uncertainty associated with some of the complex models used in planning for the COP, but no vision is laid out regarding how the monitoring plans could be used to understand, quantify, and eventually reduce modeling uncertainties. For example, COP ecological monitoring could help fill gaps in the understanding of vegetative response to restoration and provide information to improve those models. Field data should be used continuously and gradually to improve the predictive models. Conversely, models can be used to identify knowledge gaps, strategize, and optimize the design of monitoring programs (see also Chapter 6).

Improvements to the predictive models will undoubtedly increase confidence in them and facilitate the decision-making process for adaptive management in COP. These improvements, like the improvements in understanding of the system gained through comparing observations to predictions, have systemwide applications that will benefit CERP planning and programmatic adaptive management.

CONCLUSIONS AND RECOMMENDATIONS

The COP is expected to provide substantial hydrologic and ecological benefits to Water Conservation Area 3A and Everglades National Park, although the full benefits from Mod Waters and C-111 South Dade projects afforded by the plan have not been quantified. The benefits of the preferred plan are documented relative to a baseline condition of field test Increment 1.2, which itself provides substantial benefits above the prior regional operational plan, using the Mod Waters and C-111 South Dade infrastructure. The benefits provided by Increment 1.2 have not been fully quantified but are estimated to be as large as those documented for the COP. Quantifying the full benefits of the Mod Waters and C-111 South Dade projects would help stakeholders understand the expected effects of these public investments. The COP preferred alternative is projected to increase annual flow into Everglades National Park by 28 percent (relative to the Increment 1.2 baseline) and increases the percentage of flow into Northeast Shark Slough from 58 to 77 percent, more closely approximating historic flow patterns and rehydrating its wetlands. The plan is also projected to reduce tree island inundation in WCA-3 by 24 percent and provide an additional 36,000 acre-feet per year to eastern Florida Bay, mostly through the Eastern Panhandle. Habitat conditions for the endangered Cape Sable seaside sparrow are projected to improve in some areas and be negatively impacted in others. To avoid constraints on operations imposed to protect the CSSS that have limited the restoration success of previous water management plans, additional mitigation strategies may be needed to ensure that sparrows occupy new habitat created by the COP to offset anticipated losses of current sparrow habitat.

Flood risk management is the primary constraint to increased restoration benefits from the COP and is likely to pose a major limitation to increased CERP flows in the central Everglades unless additional flood risk mitigation or seepage control efforts are made. Despite large investments in land acquisition and flood mitigation projects in the 8.5 square-mile area, a residential area located west of the eastern protective levee, flood risk management in this area continues to limit restoration benefits from the COP. Although Mod Waters infrastructure was designed for a maximum L-29 Canal stage of 8.5 feet NVGD, Tamiami Trail roadway protection and flood risk management requirements for the 8.5 square-mile area currently limit the number of days the L-29 Canal can be operated at a stage above 8.3 feet NGVD. CERP projects and Tamiami Trail Next Steps are designed for a stage of 9.7 feet NVGD in the L-29 Canal. Without additional flood mitigation projects or seepage control efforts, flood risk management on the eastern edge of Everglades National Park could greatly limit the benefits of the CEPP. Efforts to expedite additional seepage management features or other flood risk management strategies will be critical to providing new water to the remnant Everglades.

The process to develop the COP was systematic and comprehensive, but three considerations could improve future planning efforts: transparency in multiobjective trade-off analysis, characterization of model uncertainty, and evaluation of performance under future conditions. The COP process involved field testing and rigorous model analyses to develop and assess alternatives using performance measures related to ecological benefits and flood risk management, covering a large area from the Water Conservation Areas to Florida Bay. However, trade-offs among various objectives and other “planning considerations and concerns,” such as flood risk management, were not transparent no well documented, leaving stakeholders unclear if ecological objectives were compromised for other considerations. Lack of characterization of model uncertainty limits the potential application of adaptive management, because when observations fall outside of model projections, it is unclear whether this is due to model error or if the system is not responding as expected. Finally, analysis of the COP under a range of possible future conditions rather than a single historical period would provide a more realistic estimate of the likely future performance.

The COP offers a remarkable opportunity to learn about restoration, inform the design and operation of CERP projects, and increase the benefits of the COP through adaptive management. The COP marks a pivot from project development to the task of optimizing the performance of new features to achieve ecological objectives under competing interests and uncertain future conditions. Effective management of the system will require assimilation of observations and expectations and adaptive responses to new information. The COP Adaptive Management and Monitoring Plan contributes to these needs. The plan was thoughtfully developed, used a logical approach to identify the highest-priority uncertainties, and provided clear monitoring thresholds that trigger additional management actions. The plan provides a framework to ensure that benefits from restoration projects are realized and offers management actions to accommodate changes in the ambient environmental conditions. Sizable potential exists for COP monitoring and assessment to inform the CERP program more broadly, particularly for the CEPP. COP monitoring data can be used to examine deficiencies in model predictions and improve the predictive capacity of modeling tools. It can also be used to reveal gaps in understanding of the ecosystem and its response to restored hydrology that have systemwide applications, including beginning to test the fundamental assumption that “getting the water right” will result in the desired ecological restoration.

Scientific expertise is essential to support COP adaptive management, but lack of staff support and dedicated resources could limit the potential benefits of the adaptive management program. A structured process to facilitate the assessment of monitoring data and effective communication with decision makers has not been identified. It will be important that modeling tools and staff be made available to analyze and learn from the COP results and determine which outcomes represent significant deviations from expectations. Experienced staff with dedicated resources will be needed to provide routine multiagency review of assessment results and develop recommendations for management. Furthermore, the evidence-based decision making required to achieve COP objectives will benefit from programmatic linkages to share decision-relevant information from other CERP projects.

5

Estuaries and Coastal Systems

The northern and southern estuaries of the Greater Everglades ecosystem are aquatic habitats that span the transition zones between the inland freshwater riverine and wetland habitats and the marine environments of the Atlantic Ocean, the Florida Keys Reef tract, and the Gulf of Mexico (Figure 5-1). Although they share similar attributes with estuaries around the world, these estuaries are unique within the continental United States due to their subtropical climate, karst geology, and connectivity to the Greater Everglades (Table 5-1). South Florida estuaries are beloved by the public and are vital to Florida's economy—supporting commercial and recreational fisheries, recreation, and tourism. However, as a direct and indirect consequence of an increasing human population, these coastal estuaries are among the most threatened natural habitats in Florida (Scott, 2004). Over the past 150 years they have been impacted by land development and structural changes (e.g., dredge and fill activities), hydromodification, pollution, climate change and sea-level rise, commercial and recreational overuse, and, recently, algal blooms, some of which are toxic.

FIGURE 5-1 Major estuaries of the South Florida ecosystem. The four estuaries examined in depth in this chapter are highlighted.

TABLE 5-1 Comparison of Key Characteristics of Four South Florida Estuaries

	Caloosahatchee	**St. Lucie**	**Biscayne Bay**	**Florida Bay**
Type	River dominated Estuary	River dominated estuary	Marine Lagoon	Estuarine Lagoon
Estuary size	Area: 65 km^2 Length: 42 km	Area: 26 km^2 Length: 11 km	Area: 1100 km^2	Area: 2200 km^2
Watershed size	3,600 km^2	2,700 km^2	2,400 km^2	6,200 km^2
Estuary size: Watershed size	0.02	0.01	0.46	0.32
Volume (in 10^6 m^3)	140	53	2200	2000
Average annual freshwater inflows (in 1000s AF)	1006	80	1685	331
Flushing time (years)	0.1	0.005-0.05	1.1	6.0
N:P in load (molar ratio)	21-25.2	11-19.7	274	260
Trophic state	Mesotrophic	Mesotrophic	Oligotrophic	Oligotrophic
Limiting nutrient	N	N	P	P, except in far western portions
Primary focus of CERP restoration	Reduce wet season high flow events; establish dry season optimum flow regime to reduce salinity intrusion	Reduce high and low flow events to optimize salinity regime; reduce loads from watershed via STAs	Improve nearshore salinity and enhance coastal ecosystems; increase flows (in full CERP)	Increase flows to eastern and central Bay to lower the frequency and extent of FB hypersalinity events and associated seagrass dieoff

NOTE: AF, acre-feet; FB, Florida Bay; N, nitrogen; P, phosphorus; STA, stormwater treatment area.
SOURCES: Buzzelli et al., 2013a; Fourqurean, 2019; Glenn, 2019; Graham et al., 2020; Ji et al., 2007.

The extensive die-off of seagrass in Florida Bay during the 1980s and the associated recurring phytoplankton blooms were early motivations for the Central and South Florida Restudy in 1996 and authorization of the Comprehensive Everglades Restoration Plan (CERP). A key CERP goal is to return more natural patterns of flow to the northern estuaries and to send more water south through the remnant Everglades and into the southern estuaries of Florida Bay and Biscayne Bay. Scientists have been monitoring, conducting research, and developing modeling tools that have supported management decisions on performance measures and targets for the northern and southern estuaries to assess the progress of CERP restoration. However, these estuaries are interconnected with and constantly evolving in response to a variety of natural and human-driven stressors. Many of these stressors are outside the direct influence of the CERP and may limit the ability of restoration to contribute to CERP goals. An excellent example of an external set of drivers is climate change (see Box 5-1), which is already affecting Florida estuaries (Figure 5-2) and will present a major challenge to the management of water, water quality, and estuarine biological resources of South Florida.

Moreover, CERP projects are coming online among a complex matrix of non-CERP actions and legal prescriptions that can affect both the Everglades and South Florida estuaries. A broad array of federal and state programs and uses are pursuing sometimes overlapping but often independent purposes and goals that affect the estuaries (Table 3-6). For example, water quality compliance under the Clean Water Act is a state responsibility, although water quality is a critical driver of estuarine conditions and essential to meet CERP goals for seagrass and oysters (see Box 3-1). Within each South Florida estuary, it is presently unclear what role the CERP can play in addressing pressing environmental problems and what additional actions, either through future unplanned CERP projects or through non-CERP efforts, are necessary to mitigate those problems. In this chapter the committee sought to synthesize the following for the northern estuaries (Caloosahatchee River Estuary and the St. Lucie Estuary) and the southern estuaries (Florida Bay and Biscayne Bay):

BOX 5-1 Impacts of Climate Change on Estuaries in the South Florida Ecosystem

Climate change is an example of a suite of external (global) drivers that is expected to affect estuarine resources worldwide (Figure 5-2) and will challenge management of water, water quality, and estuarine biological resources of South Florida. Sea-level rise will increase saltwater intrusion into inland aquifers, compromising drinking water supplies and complicating flood control; it may exacerbate peat loss in natural systems, leading to subsidence. Sea-level rise will also increase salinities and increase mean depths of estuaries, changing the distribution of habitat for key estuarine biota. Drastic changes in the temporal patterns of precipitation and its quantity and intensity will increase variability and uncertainty in the South Florida hydrologic cycle, complicating water resource management for both natural and developed systems. These changes will increase extreme conditions in the estuaries, such as hypersalinity or "washout" events that are deleterious to seagrass and oysters. Increases in temperature can cause a myriad of effects, including stimulating algal blooms and deoxygenation, which can result in range shifts in commercial and recreational fisheries, increased probability of seagrass die-off events, extirpation of sensitive taxa, or expansion or intensification of toxic harmful algal blooms. Climate change acidifies estuarine water, impairing the carbonate shells of bivalves, echinoderms, crabs, and other shellfish and alters biogeochemical cycles that impact seagrass growth and sediment accumulation patterns in Florida Bay. Anticipated impacts from climate change may work synergistically or antagonistically with CERP restoration projects.

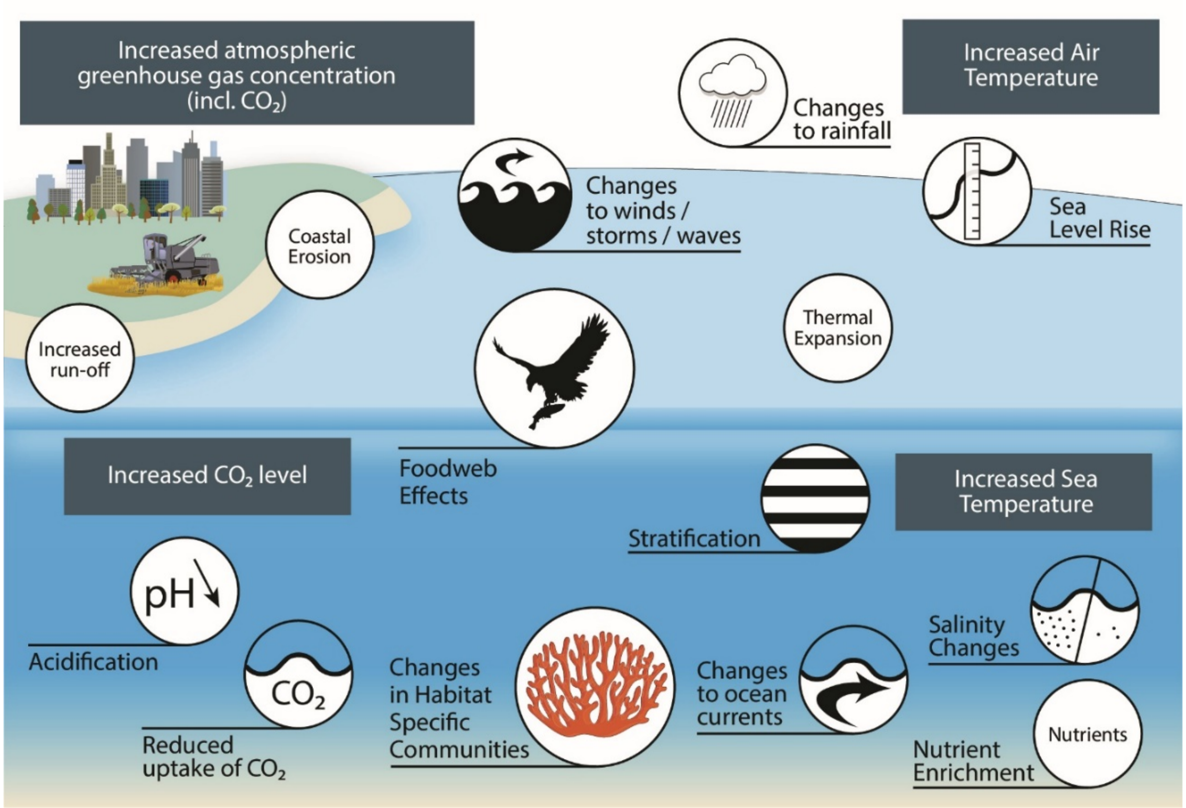

FIGURE 5-2 Conceptual model of impacts of global climate change on Florida estuaries. SOURCE: adapted from OSPAR, 2010.

- Key environmental problems facing each estuary;
- Projections of what CERP projects will do to help resolve these issues, and potential mismatches in stakeholder expectations for the CERP;
- Key questions facing CERP and non-CERP decision makers regarding restoration of the estuaries; and
- Critical science needs (e.g., observations, synthesis, models) to inform these management decisions, which could be addressed in collaboration between CERP and non-CERP agencies.

In the next section on the northern estuaries, these topics are addressed in an integrated format because of the similarities between the estuaries. Then, discussions of these topics follow for Biscayne Bay and Florida Bay.

NORTHERN ESTUARIES

The northern estuaries include the Caloosahatchee River Estuary, Estero Bay, and southern Charlotte Harbor on the west coast and the St. Lucie Estuary, southern Indian River Lagoon, Lake Worth Lagoon, and Loxahatchee River Estuary on the east coast (Figure 5-1). These estuaries are hotspots of biological diversity and also fuel productive South Florida coastal economies; for example, the St. Lucie Estuary and Indian River Lagoon supported an estimated $7.6 billion in total annual direct economic output from activities such as tourism, fisheries, and marine industries (East Central Florida and Treasure Coast Regional Planning Council, 2016). Among these seven northern estuaries, the Caloosahatchee River and St. Lucie Estuaries are the most directly impacted by Lake Okeechobee water releases and numerous CERP projects. In this section, the committee describes environmental changes to the Caloosahatchee River and St. Lucie Estuaries and near-term CERP progress toward restoration goals, identifies key questions in northern estuaries restoration management, and reviews the adequacy of science to support these decisions.

Environmental Changes and Their Ecological Effects

Structural and hydrologic changes in the Caloosahatchee River and St. Lucie Estuaries and watersheds have resulted in substantial water quality changes and ecological impacts in the estuaries.

Caloosahatchee River Estuary

The Caloosahatchee River Estuary is a river-dominated estuary some 42 km in length (Figure 5-3). Its watershed encompasses approximately 3,600 km^2 (1,400 mi^2). Under predrainage conditions, no navigable connection existed between the Caloosahatchee River and Lake Okeechobee, although during rainy periods, some Lake Okeechobee water overflowed into the headwaters of the Caloosahatchee River (Steinman et al., 2002). More than 150 years ago, the Caloosahatchee River Estuary was home to abundant beds of brackish water seagrass (*Vallisneria americana*) in the low-salinity zones in the upper estuary and marine seagrasses (*Thalassia testudinum*, *Halodule wrightii*) near the estuary mouth (Figure 5-3). These beds retained sediments, attenuated wave action, improved water clarity and quality, and hosted an abundance of aquatic life including fish, shellfish, aquatic mammals, freshwater turtles, and birds (CHNEP, 2016; FWC, 2016; FWS, 2016b). Under predrainage conditions, extensive oyster bars and shoals covered the lower estuary (Sackett, 1888). A rich spawning and nursery habitat for invertebrates and finfish supported economically important recreational and commercial fisheries, contributing to Ft. Myers' fame as a tourism and sportfishing magnet (Kokomoor, 2012). The estuary continues to provide forage and breeding grounds for resident and migratory birds and marine mammals; more than 40 state and federally threatened and endangered species utilize the Caloosahatchee River Estuary as critical habitat, including the iconic West Indian manatee (CHNEP, 2016).

Structural and hydrologic changes. Many of the ecological problems in the Caloosahatchee River Estuary are a result of high variability in seasonal and interannual freshwater discharge and the structural changes within the estuaries and their respective watersheds that took place over the past century. In the Caloosahatchee River watershed, riverine hydrology was radically altered, starting in the 1880s when the river was deepened and straightened (Antonini et al., 2002). By 1918, a combination of locks and spillways was added to the river, from the Franklin Lock and Dam (S-79), which now forms the upstream head of the estuary, to the S-77 outflow structure, which connected the headwaters of the Caloosahatchee River to Lake Okeechobee (Figure 5-3). This hydrologic connection to Lake Okeechobee expanded the estuary's watershed[1] and increased the occurrence of high-volume flows. Over the past two decades, on average, contributions from the local watershed represented the majority of the inflows to the estuary (Figure 5-4), but Lake Okeechobee regulatory releases have contributed up to 43 percent of total flows in recent wet years (see Figure 3-21; Serna et al., 2020). In the 1960s navigation channels were dredged, creating a conduit for migration of saltwater up the estuary, and historic oyster bars were mined for road construction (Chamberlain and Doering, 1998; SFWMD, 2018a; Sun et al., 2016). River channelization, wetland drainage, and urban and agricultural development reduced natural water storage throughout the watershed and altered the amount and timing of freshwater flow into the estuary. These changes dramatically altered mesohaline and polyhaline habitats of the mid and lower estuary, which have important consequences for its ecology and water quality (Graham et al., 2020).

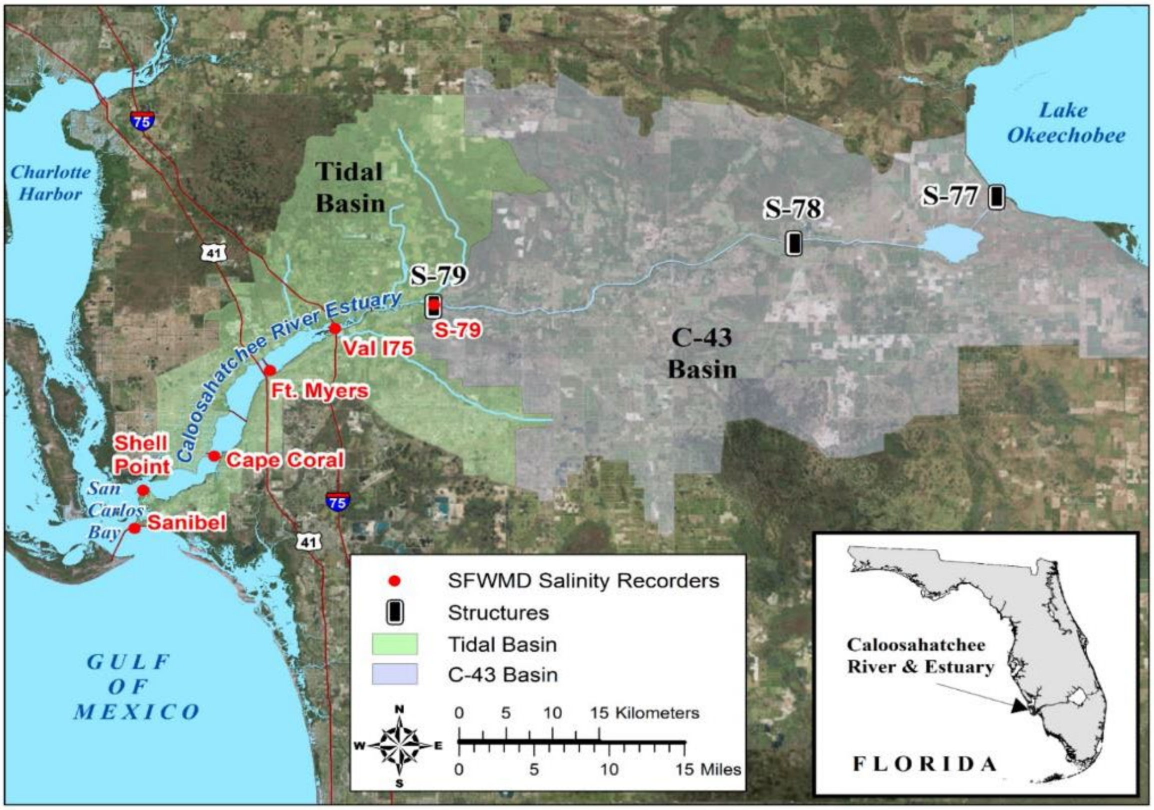

FIGURE 5-3 Caloosahatchee River watershed, including the estuary, the major watershed basins, and major water control structures. SOURCE: Glenn, 2019.

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[1] The SFWMD does not include Lake Okeechobee or the Kissimmee River basin as part of the delineated area of the estuary watershed.

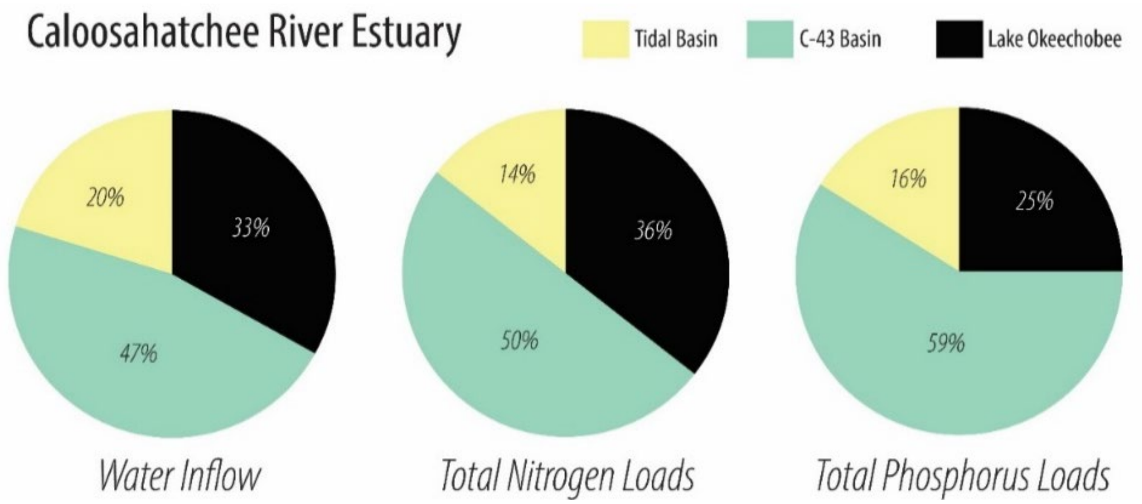

FIGURE 5-4 Percentages of the sources (tidal basin, Caloosahatchee River basin, and Lake Okeechobee) of water inflows and total nitrogen and total phosphorus loads into the Caloosahatchee River Estuary based on long-term (1997-2019) water year averages. SOURCE: Data from Serna et al., 2020.

Ecological and water quality implications. These structural and hydrologic changes have modified salinity regimes and caused decline in water quality in ways that fundamentally altered suitable habitat for brackish water and marine seagrass, oysters, plankton, and fish in the Caloosahatchee Estuary (Barnes, 2005; Chamberlain and Doering, 1998). Extended high wet season discharges to the Caloosahatchee River Estuary reduce salinities, causing mortality of oysters and marine seagrasses in the lower estuary, while associated high colored dissolved organic matter (CDOM)[2] throughout the estuary limit light penetration, inhibiting *Vallniseria* growth (Chamberlain and Doering, 1998; Doering et al., 2002; Volety et al. 2009). Areas that were dredged and deepened would preclude seagrass, particularly when coupled with lower light availability. Harris et al. (1983) estimate a loss of 87 percent of marine seagrass from the lower estuary. Extremely low salinities from these discharges are also thought to be responsible for the presence of the fungus *Aphanomyces invadens* and the occurrence of fish with lesions in the Caloosahatchee River Estuary (Sosa et al., 2007).

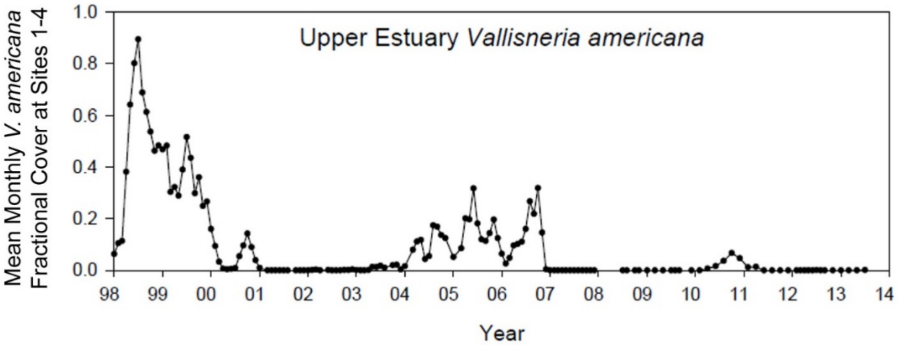

FIGURE 5-5 Mean monthly proportion cover of *Vallisneria americana* from monitoring sites in the upper Caloosahatchee River Estuary from 1998 to 2013. 1.0 = 100% cover. After 2014, seagrass monitoring methodologies were modified; from 2014 to 2017 average percent cover of *V. americana* remained < 5%. The loss of *Vallisneria* occurred during a severe drought in 2000-2001, with a partial reestablishment occurring from 2004 to 2006. Since 2006, *Vallisneria* has been sparse to nonexistent after repeated drought events in 2007-2008 and 2011. SOURCE: RECOVER, 2014.

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[2] Although CDOM is comprised of naturally occurring organic matter, developed land uses including draining and clearing of wetlands and adjacent riparian habitat can greatly augment CDOM.

Conversely, low dry season freshwater discharges and associated high salinity in the upper estuary caused die-back of *Vallniseria* beds. Periods of low flow in the 2000s resulted in the loss of the majority of *Vallniseria* acreage (Figure 5-5), and even when salinity conditions have been within tolerance ranges, revegetation has been hampered by reduced dispersal (Graham et al., 2020). In the dry season without sufficient freshwater inflows, saltwater migrates all the way up the estuary to the S-79 structure, truncating the salinity gradient and compressing estuarine habitat for estuarine plankton and fish (SFWMD, 2017), increasing predation and competition for food resources, and lowering growth and survival (Eby and Crowder, 2002; Peterson, 2003; SFWMD, 2018a). Low flows and salinity intrusion

BOX 5-2 Harmful Algal Blooms in the Northern Estuaries

Periodic blooms of marine (e.g., red tide species *Karenia brevis*) and freshwater harmful algal blooms (HABs, e.g., photosynthesizing cyanobacteria, commonly called blue-green algae) are a major problem within the St. Lucie and Caloosahatchee River Estuaries. In October 2017, the southwest coast experienced one of the worst red tides in recent history; millions of pounds of fish, dolphins, manatees, and other sea life washed ashore (Perkins, 2019). While *Karenia* blooms originate offshore, blooms can intensify inshore and within estuaries, when fueled by high nutrient concentrations (Anderson et al., 2008). Recent analyses suggest that bloom dynamics observed near Charlotte Harbor, Florida, between 2012 and 2018 were systematically influenced by nitrogen concentrations measured at the discharge point of the Caloosahatchee River (Medina et al., 2020) and suggest that bloom events would be mitigated by nitrogen source and transport controls within the Caloosahatchee and/or Kissimmee River basins.

Toxic cyanobacterial blooms have been recurring in Lake Okeechobee in recent years, with tremendous impacts on the northern estuaries. Cyanobacteria *Microcystis spp*. and *Dolichospermum spp*., in addition to their odor and unsightly algal mats, can produce microcystins and saxitoxins, which act as liver toxins or neurotoxins and are deleterious to human health, aquatic life, livestock, and pets (Dreher et al., 2019; Harke et al., 2016). As cyanobacterial cells are transported downstream from Lake Okeechobee into estuarine habitat or are produced *in situ* in low-salinity zones, they are consumed by shellfish, invertebrates, and fish, where they bioaccumulate, poisoning marine mammals (Miller et al., 2010) or humans that consume these contaminated food sources. In 2016, a large cyanobacterial bloom on Lake Okeechobee seeded a bloom that expanded throughout the St. Lucie River and Estuary (Figure 5-2-1), leading Florida to declare a state of emergency that lasted for 242 days (Kramer et al., 2018). In 2018, a record rainfall produced extensive blooms in Lake Okeechobee and both estuaries.

FIGURE 5-2-1 Algae bloom in the St. Lucie River Estuary, June 24, 2016. SOURCE: Eric Hasert, Treasure Coast Newspapers.

into the upper estuary enhance stratification, which exacerbates the potential for algal blooms and low dissolved oxygen. Oyster production has generally been low, because the life cycle is impacted by both low and high salinities (i.e., < 10 or > 30 practical salinity units [PSU]; SFWMD, 2020; Volety et al., 2009).

Structural, hydrologic, and land use alterations in the watershed and estuary have promoted water quality conditions that have caused low dissolved oxygen in some local tidal basins; reduced water clarity, which diminishes aesthetics and light required for seagrass growth; and, more recently, supported recurring toxic harmful algal blooms (HABs; see Box 5-2). In 2009, a total maximum daily load (TMDL) was established to limit nitrogen loading from the Caloosahatchee River watershed associated with low dissolved oxygen (see Chapter 3 for discussions of recent water quality relative to the TMDL), but the TMDL did not address water clarity or HABs, which have more recently emerged as key environmental problems. CDOM is the most important factor limiting water clarity, and increased freshwater flows to the estuary are associated with increases in CDOM (Figure 5-6; Buzzelli et al., 2014a; Chen et al., 2015). Increased flows and nutrient loads and water column stratification are among the factors known to promote freshwater cyanobacterial blooms (Paerl and Otten, 2013) and marine HABs such as *Karenia brevis* (Medina et al., 2020). Although the Caloosahatchee watershed is the largest source of nutrient inputs (Figure 5-4; see also Chapter 3), discharges from Lake Okeechobee are an additional source of nutrients and may also seed populations of cyanobacteria (Phlips et al., 2012). Climate change exacerbates factors that lead to increased HAB frequency, such as warm temperatures, high irradiance, and high carbon dioxide (Burford et al., 2020; Hallegraeff, 2010). As climate change shortens the duration of the cooler seasons, the frequency of HABs in inland and coastal waters is expected to increase (see Box 5-1; Chapra et al., 2017).

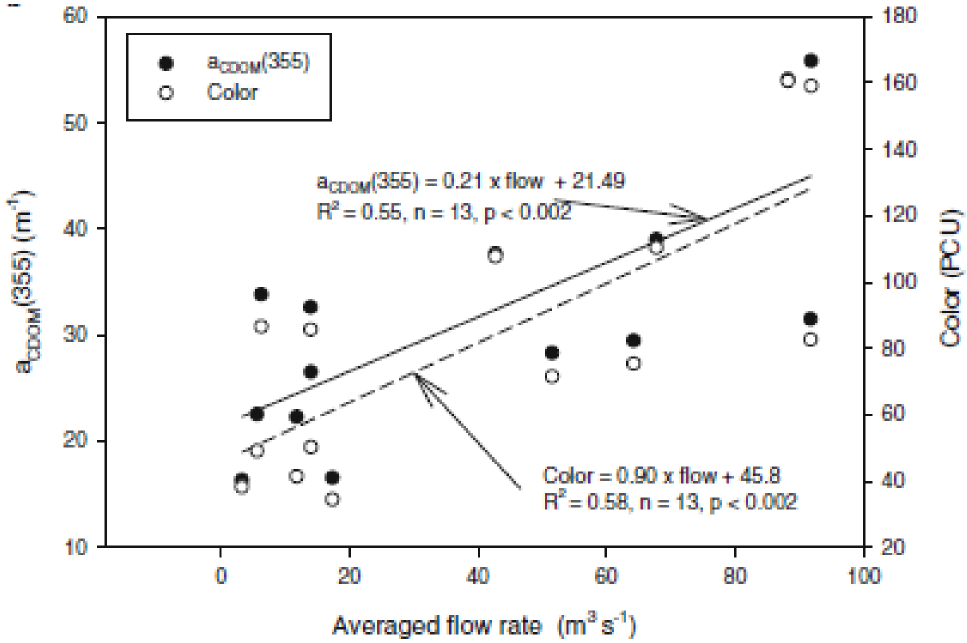

FIGURE 5-6 Relationship of visual water color (right y axis, open circles) and its proxy colored dissolved organic matter (CDOM) absorbance (left y axis, solid circles) with freshwater flow in the Caloosahatchee River Estuary. Under low flow, the estuary is dominated by a high volume of ocean waters that are high in salinity and low in color. SOURCE: Chen et al., 2015.

St. Lucie Estuary

To the east of Lake Okeechobee, the St. Lucie Estuary is a river-dominated estuary, extending 11 km long to its outlet to southern Indian River Lagoon, through which it connects to the Atlantic Ocean (Figure 5-7). However, in the mid- to late 1800s, the St. Lucie was a freshwater lagoon, embedded in a mosaic of freshwater wetlands and upland prairie with an ephemeral connection to the Indian River Lagoon (SFWMD, 2002). In 1892, an inlet was permanently dredged, converting the freshwater lagoon to a brackish water estuary (Osborne, 2016; SFWMD, 2002). Like the Caloosahatchee, 100 years ago the St. Lucie Estuary and the nearby southern Indian River Lagoon were home to abundant marine and brackish-water seagrass meadows and oyster beds. This estuary and its adjacent marine lagoon fostered a rich and biologically diverse flora and fauna including more than 2,000 species of plants, 600 species of fish, and 300 species of resident and migratory birds, including 53 threatened or endangered species (Osborne, 2016). During the early 20th century, the St. Lucie–Indian River Lagoon estuarine complex was renowned for its recreational and commercial fisheries, including clams, crabs, oysters, shrimp, and finfish (e.g., inshore tarpon). These fisheries were key elements that attracted tourism and urban development, leading to the nickname, “The Treasure Coast” (Osborne, 2016).

Structural and hydrologic changes. Like the Caloosahatchee River Estuary, the St. Lucie Estuary has a long history of structural alterations and water quality changes, with parallel yet distinct biological consequences. In 1916, the C-44 Canal was constructed, connecting Lake Okeechobee to the South Fork of the St Lucie (Figure 5-7). With the accompanying boom in agriculture and urban

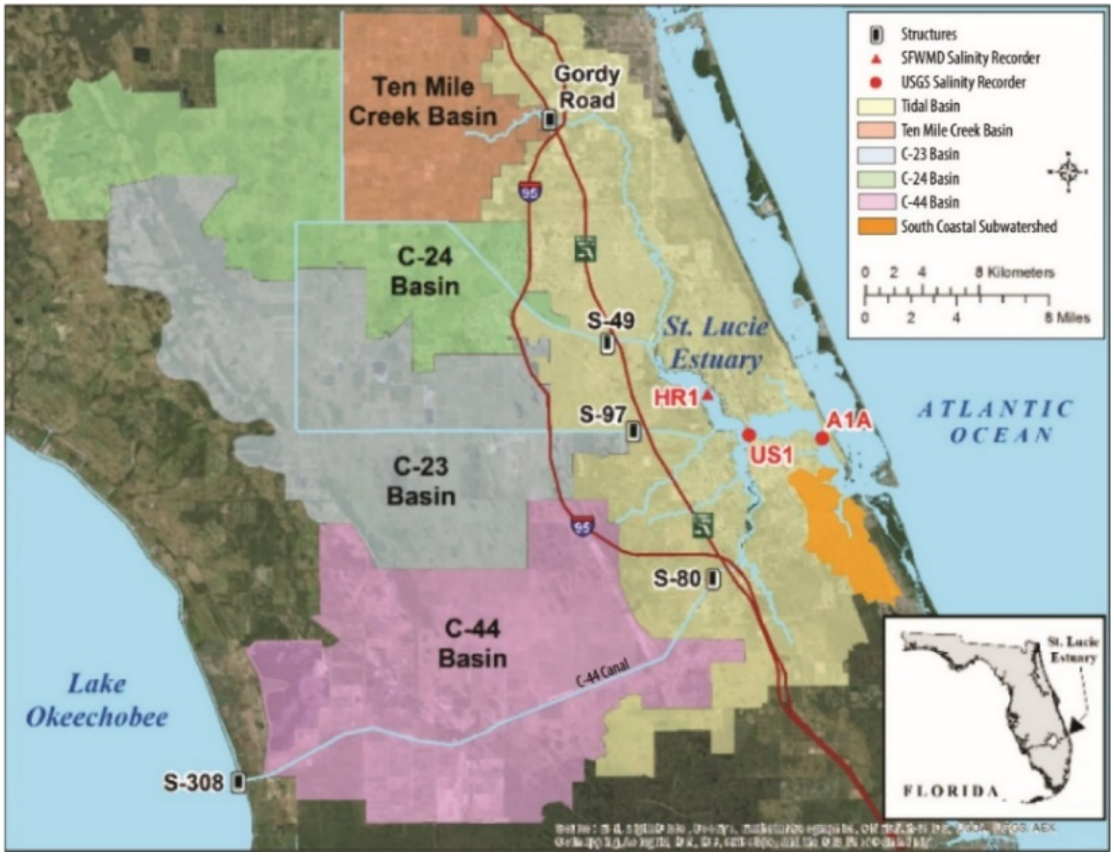

FIGURE 5-7 St. Lucie Estuary and watershed with its basins and major water control structures. The St. Lucie mouth opens to the southern end of the Indian River Lagoon, which then opens to the Atlantic Ocean. The St. Lucie watershed includes the St. Lucie Basin (consisting of the Ten Mile Creek, C-24, C-23, and C-44 Basins) and the Tidal Basin. SOURCE: Modified from Glenn, 2019.

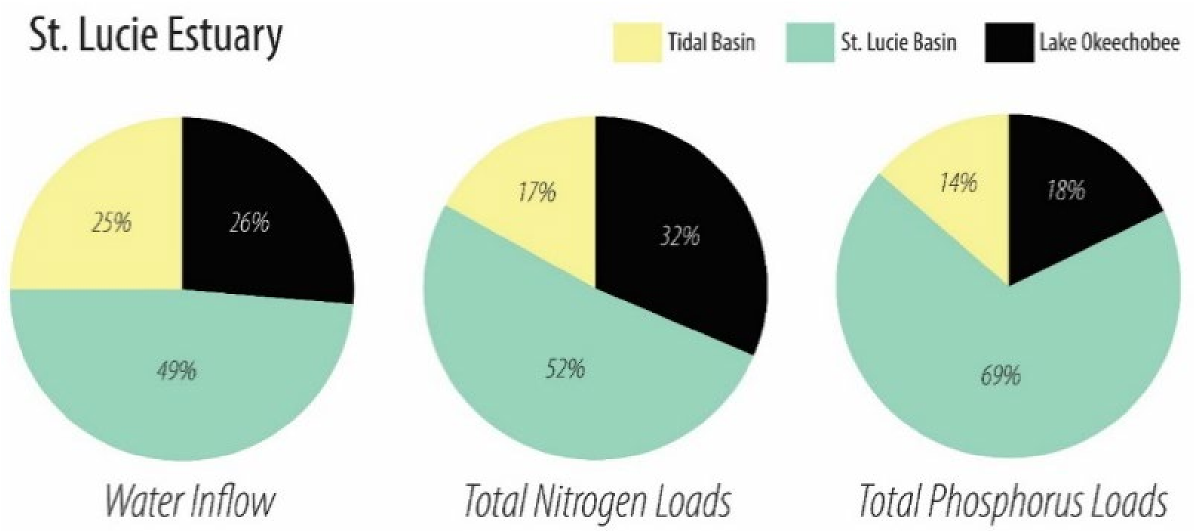

FIGURE 5-8. Percentages of the sources (tidal basin, St. Lucie basin, and Lake Okeechobee; see Figure 5-7) of water inflows and total nitrogen and total phosphorus loads into the St. Lucie Estuary based on long-term (1997-2019) water year averages. Totals shown may exceed 100 percent due to rounding. SOURCE: Adapted from Serna et al., 2020.

development, the natural watershed was drained and interconnected, expanding the St. Lucie watershed area three-fold (SFWMD, 2002; Sime, 2005). The expanded drainage area created a watershed-to-estuarine area ratio that is 100 to 1,000 times higher than is typical of estuarine environments around the world—an extreme outlier (Table 5-1; Dürr et al., 2011). The canal drainage system greatly reduced natural water storage in the St. Lucie watershed, exacerbating floods and drought conditions in the estuary. Operation of the Lake Okeechobee regulatory releases for flood control combined with the basin drainage system significantly altered the magnitude and timing of freshwater flow into the St. Lucie, with the lake contributing about 26 percent of the total inflow (Figure 5-8), whereas historically the estuary was not connected to the lake. Natural shorelines of the St. Lucie Estuary were also developed and hardscaped to prevent erosion from boat traffic.

Water quality and ecological impacts. As with the Caloosahatchee River Estuary, wet season watershed runoff and Lake Okeechobee regulatory releases bring extreme fluctuations in St. Lucie Estuary salinity and plumes of associated suspended sediment, nutrients, and CDOM (Chen et al., 2015; Sime, 2005). CDOM and turbidity are a major water quality issue, because they limit light to the estuary bottom. Together with highly variable salinity, these water quality changes have caused a tipping point, converting the estuary from a seagrass-dominated habitat to a plankton-dominated ecosystem (Graham et al., 2020; Sime, 2005). The composition of the phytoplankton community is strongly controlled by freshwater discharges and associated nutrients from the St. Lucie Basin and Lake Okeechobee and is intermittently dominated by toxic HABs (see Box 5-2; Badylak et al., 2015). Local watershed inputs from the St. Lucie Basin are a more significant source of nutrient loading and CDOM than Lake Okeechobee (Figure 5-8; Walsh, 2017). The Florida Department of Environmental Protection (FDEP) established a TMDL for nitrogen and phosphorus loading for the St. Lucie watershed to achieve nutrient and dissolved oxygen criteria in the estuary (FDEP, 2008), but the TMDL was not specifically intended to address HABs.

High CDOM and sediment plumes from freshwater discharges limit seagrass extent as far seaward as the southern Indian River Lagoon (IRL; Buzzelli et al., 2012). High sedimentation events from the watershed cause muck deposits in the estuary, resulting in unsuitable substrates for oysters, benthic invertebrates, and seagrass. These sediments have a high oxygen demand, creating occasional hypoxia events in the estuary (Buzzelli and Doering, 2019; FDEP, 2008), and contain concentrations of trace metals that are potentially harmful to fish and invertebrates (Sime, 2005). Collectively, by the mid-20th century, these habitat changes led to a collapse of the historic and world-renowned inshore tarpon fishery that relied on the native food web (Osborne, 2016). Over the past several decades, these conditions, particularly low-salinity events, have caused a loss of approximately 85 percent of native oyster habitat, from a historical extent of 567 hectares (1,400 acres; Sime, 2005). Current oyster production in the remaining habitat shuts down during low-salinity events.

Restoration Goals and Expected Effects of Planned CERP Projects

The 2007 Interim Goals Agreement (USACE et al., 2007) describes the early qualitative CERP hydrologic and ecological goals for the Caloosahatchee River and St. Lucie Estuaries. These CERP goals aimed to increase American oyster and seagrass habitat by managing flow regimes to improve salinities for those habitats. Specifically, the Interim Goals aimed to reduce the occurrence and duration of high-volume flows (> 2,800 cubic feet per second [cfs] in the Caloosahatchee and > 2,000 cfs in the St. Lucie) as well as low-volume flows (< 450 cfs in the Caloosahatchee and < 350 cfs in the St. Lucie), measured as monthly averages. To track restoration progress and understand factors underlying observed changes, RECOVER monitors oysters (density, reproduction and recruitment, disease) and seagrass (species occurrence, cover, density) as well as other biological and water quality indicators including salinity and water clarity (CDOM, turbidity) (RECOVER, 2019). CERP planners did not explicitly consider water quality or harmful algal blooms when establishing these 2007 goals.

Several CERP projects (USACE and SFWMD, 1999) improve the ability to manage the magnitude and timing of freshwater flow to the northern and southern estuaries, and most of these have now been planned (Table 5-2; see also Chapter 3 for project descriptions and progress to date). These planned projects enhance water storage to the north, south, east, and west of Lake Okeechobee, including large aboveground reservoirs and belowground storage using aquifer storage and recovery (ASR). Collectively, these projects include about 676,000 acre-feet of aboveground storage capacity and 80 ASR wells with the potential for each to inject or withdraw 5 million gallons per day into the subsurface. The potential for additional storage in the development of the new Lake Okeechobee System Operating Manual remains the largest unresolved element affecting the northern estuaries (see Chapter 3).

CERP Projects That Affect the Caloosahatchee River Estuary

The three primary CERP projects that are expected to improve conditions in the Caloosahatchee River Estuary are the C-43 Reservoir, the Central Everglades Planning Project (with Everglades Agricultural Area [EAA] Reservoir), and the Lake Okeechobee Watershed Restoration Project. As of January 2021, of these three, only the Lake Okeechobee Watershed Restoration Project has not yet been authorized. Collectively, the projects are predicted to reduce the number of high-volume mean monthly flows (>2,800 cfs) to the Caloosahatchee Estuary by 43 percent and very-high-volume mean monthly flows (>4,500 cfs) by 72 percent. These projects collectively meet the performance originally predicted for the CERP (termed here as the CERP goal; see Table 5-3), which emphasized reduction of high flows from Lake Okeechobee over basin flows.

Planned and approved CERP projects will have a larger effect on low-flow events in the Caloosahatchee River Estuary. CERP projects are projected to reduce the number of mean monthly flows below 450 cfs by about 70 percent, although further performance improvements may be feasible with changes to Lake Okeechobee operations (W. Wilcox, South Florida Water Management District [SFWMD], personal communication, 2020). If future changes in Lake Okeechobee operations (see Chapter 3) reduce the availability of freshwater to the estuaries during dry periods, the predicted project performance could be reduced. The stated ecosystem restoration target is zero low-flow events (Table 5-3).

TABLE 5-2 Planned CERP Projects Affecting the Northern Estuaries

Storage Component	Storage Capacity (acre-feet)	Maximum Annual Storage Capacity (acre-feet/year)
Aboveground Reservoirs		
Lake Okeechobee Watershed Restoration Plan	46,000[a]	
C-43 Reservoir	170,000	
Indian River Lagoon-South[c]	160,000[b]	
Central Everglades (includes EAA Reservoir)	300,000[c]	
ASR Wells		
Lake Okeechobee Watershed Restoration Plan		448,000[a]

[a] Based on tentatively selected plan for the Lake Okeechobee Watershed Restoration Project as of January 2020.
[b] Includes C-44, C-23, C-24, C-25, and St. Lucie North and South Fork reservoirs and natural storage areas.
[c] Includes Everglades Agricultural Area (EAA) Reservoir and A-1 flow equalization basin, which was constructed for Restoration Strategies.
SOURCES: NRC, 2005; USACE and SFWMD, 1999, 2004b, 2010, 2014.

TABLE 5-3 Predicted Effects of CERP Projects on the Number of Months with High and Low Flows in the Caloosahatchee Estuary Based on a 41-Year Period of Record

	Number of months with high-volume mean monthly flows (>2,800 cfs)	Number of months with very high vol. mean monthly flows (>4,500 cfs)	Number of months with low mean monthly flows (<450 cfs)
Existing conditions baseline (2014)	94[a]	43[b]	116[a]
C-43	81[a]	33[b]	27[a]
C-43+CEPP	70[a,c]	29[c]	23[a]
C-43+CEPP PACR	61[c]	24[c]	26[d]
C-43+CEPP +LOWRP	60[e]	25[e]	24[e]
C-43+CEPP PACR+LOWRP	54[f]	12[f]	37[f,g]
CERP goal	81% reduction in lake-triggered events (56 total)[h]		
Restoration target	0[d]	0[d]	0[d]

NOTES: Output from several different model runs based on 1965-2005 precipitation data. Output reflects on the number of months meeting criteria out of the 41-year (or 492-month) period of record used in the analyses. The model runs presented here may not have the exact same conditions from project to project, but the output collectively is presented for general trends. CEPP, Central Everglades Planning Project; LOWRP, Lake Okeechobee Watershed Restoration Project; PACR, Post Authorization Change Report.
SOURCES:
[a] USACE and SFWMD (2014, Figure G-28).
[b] USACE and SFWMD (2014, Figure 6-7).
[c] USACE (2020a, Table 3-3).
[d] USACE (2020a Figure 3-4).
[e] USACE and SFWMD (2019, Chap. 6).
[f] W. Wilcox, SFWMD, personal communication, 2020.
[g] "This 'reversal' in low flow performance here can be overcome with Lake [Okeechobee] operations – see CERP Component E5." (W. Wilcox, SFWMD, personal communication, 2020).
[h] The CERP goal, as defined by the RECOVER CERPA model run compared to existing-conditions baseline (ECB), using data from 1965-2000, is an 81% reduction in lake-triggered events. Using data from 1965-2005, this represents 56 months of high-volume flows, with approximately 47 months triggered by local basin flows (W. Wilcox, SFWMD, personal communication, 2020).

TABLE 5-4 Predicted Effects of CERP Projects on the Number of 14-Day Periods or Months with High and Low Flows in the St. Lucie Estuary Based on a 41-Year Period of Record

	Number of high-volume 14-d moving average flows (>2,000 cfs)	**Local basins only:** number of high-volume 14-d moving average flows (>2,000 cfs)	**Lake O. reg. releases only:** number of high-volume 14-d moving average flows (>2,000 cfs)	Number of months with low mean monthly flows (<350 cfs)
Existing-conditions baseline (2014)	177[a]	105[a]	72[a]	89[a]
IRL-S	151[a]	86[a]	65[a]	92[a]
IRL+CEPP	86[a]	50[a]	36[a]	65[a] or 83[e]
IRL+CEPP PACR	71[d]	49[d]	22[d]	67[d]
IRL+CEPP+LOWRP	71[e]	52[e]	19[e]	83[e]
IRL+CEPP PACR+LOWRP	60[f]	47[f]	13[f]	71[f]
CERP goal			81% reduction in events[g]	
Restoration target	0[a]			31[b]

NOTES: Output from several different model runs based on 1965-2005 precipitation data. These models may not use the exact same assumptions, but the output collectively is presented for general trends. CEPP, Central Everglades Planning Project; IRL-S, Indian River Lagoon-South; LOWRP, Lake Okeechobee Watershed Restoration Project; PACR, Post Authorization Change Report.
SOURCES:
[a] USACE and SFWMD (2014, Figure G-29).
[b] USACE and SFWMD (2014, Figure 6-8).
[d] USACE (2020a, Figure 3-5).
[e] USACE and SFWMD (2019, Chap. 6).
[f] W. Wilcox, SFWMD, personal communication, 2020.
[g] The CERP goal, as defined by the RECOVER CERPA model run compared to ECB, using data from 1965-2000, is an 81% reduction in lake-triggered events (W. Wilcox, SFWMD, personal communication, 2020).

CERP Projects That Affect the St. Lucie Estuary

As in the Caloosahatchee, the central objective of the CERP for the St. Lucie Estuary is to reduce the occurrence and duration of harmful high- and low-volume discharges. Three CERP projects are expected to have significant effects on the St. Lucie: the Indian River Lagoon-South Project, the Central Everglades Planning Project (with EAA Reservoir), and the Lake Okeechobee Watershed Restoration Project (Table 5-2). Results of model simulations show that these projects are expected to reduce the overall number of 14-d periods with high flows in the St. Lucie Estuary (14-d moving averages over 2,000 cfs) by 66 percent and the number of high-flow periods resulting from Lake Okeechobee regulatory releases by 82 percent (Table 5-4). The projects collectively are predicted to be more successful at reducing the number of high-flow events from Lake Okeechobee compared to those from local basin runoff (55 percent reduction).

The planned and approved CERP projects appear less successful at reducing the frequency of low-flow conditions in the St. Lucie Estuary. Collectively, the CERP projects in Table 5-2 provide a 20 percent reduction in the number of months with flows < 350 cfs compared to an ecosystem restoration target of 66 percent reduction (Table 5-4).

Finally, the Indian River Lagoon-South project includes 8,700 acres of stormwater treatment areas (STAs), which is expected to reduce nutrient loads to the St. Lucie Estuary. Though these projections are dated, the USACE and SFWMD (2004b) state that the STAs would reduce phosphorus loads by 18 percent and nitrogen loads by up to 8 percent compared to the 2050 conditions without the project. Considering all aspects of the project, including nutrient removal due to natural land restoration, increased irrigation, and passive removal in the reservoir, the project was expected to reduce phosphorus loads to the St. Lucie Estuary by 35 percent and nitrogen loads by 24 percent compared to the 2050 conditions without the project.

Overall Effects from Planned CERP Projects on the Northern Estuaries

As noted previously, the majority of flows and nutrient loads to the Caloosahatchee River and St. Lucie Estuaries drain from local basins, with the remainder from Lake Okeechobee (Figures 5-4 and 5-8). Thus, while planned CERP projects are projected to reduce the number of Lake Okeechobee–triggered high-flow events by 80 percent, the overall reduction in the number of high-volume mean monthly flows is projected to be only 43 percent for the Caloosahatchee River Estuary and 66 percent for the St. Lucie Estuary. Planned CERP projects are predicted to reduce the number of mean monthly low-volume flows for the Caloosahatchee River and St. Lucie Estuaries by 70 and 20 percent, respectively.[3] Thus, both the St. Lucie and Caloosahatchee are expected to continue to receive damaging high-volume discharges, primarily from their local watersheds, and face low-flow conditions with planned CERP projects. Based on estimated storage needs from Graham et al. (2015), an additional 230,000 acre-feet of storage in the Caloosahatchee River watershed, 40,000 acre-feet in the St. Lucie Basin, and at least 200,000 acre-feet north and/or south of Lake Okeechobee[4] beyond currently planned projects would be needed to reduce high flows to the northern estuaries. Additionally, with the exception of the STAs in the IRL-S project, the CERP will not address nutrient concentrations in the remaining flows, although overall nutrient loads from Lake Okeechobee are expected to be reduced. The shortage in storage to address the local runoff from highly altered watersheds may prevent CERP from reaching its ecological restoration goals.

Implications of Environmental Issues for CERP and Non-CERP Efforts

In the next several years, new CERP storage projects with the potential to improve conditions in the northern estuaries will come online along with the completion of the Herbert Hoover Dike around Lake Okeechobee. Additional CERP and non-CERP projects are also planned in the estuary watersheds over the next decade. The benefits of these projects will depend on their optimized operations, potentially affecting water supply, water quality, HABs, fisheries, aesthetics, and ecotourism, among others.

The CERP and agencies working to restore the northern estuaries have a fundamental challenge: the public is demanding immediate action to eliminate harmful algal blooms, while also expecting that the CERP will restore seagrass and oyster habitat, while balancing water resource needs and flood risk management for a thriving South Florida economy (Figure 5-9; Graham et al. 2015). Currently, major decisions on the operations of Lake Okeechobee and its water releases are made without a quantitative understanding of the effects of those decisions on water quality and harmful algal blooms. Additionally, the approaches used by the CERP to estimate optimal freshwater flows for oyster and seagrass habitat restoration (RECOVER, 2020) primarily rely on salinity tolerance ranges and are lacking additional fundamental habitat and water quality constraints that will ultimately limit their distribution (e.g., sediment quality, nutrients, algal blooms, turbidity, water color).

On the flip side, water quality is inextricably linked to flow, so water quality managers must understand how water releases associated with CERP projects will impact water quality and attainment of TMDLs. For example, nutrient TMDL targets established for both the Caloosahatchee River and St. Lucie Estuaries do not consider the ecological consequences of CERP-controlled flows causing a seasonal

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[3] Expected outcomes would change with system operations (including management of Lake Okeechobee) that differ from those modeled.

[4] Graham et al. (2015) estimated that a total of 400,000 acre-feet of storage in the Caloosahatchee River watershed, 200,000 acre-feet in the St. Lucie River watershed, and approximately 1 million acre-feet of surface storage north and south of Lake Okeechobee would be needed to reduce damaging estuary discharges. Estimates of storage gaps are calculated based on totals in Table 5-2, with an understanding that maximum annual subsurface storage volumes may not equate to surface storage volumes in terms of benefits.

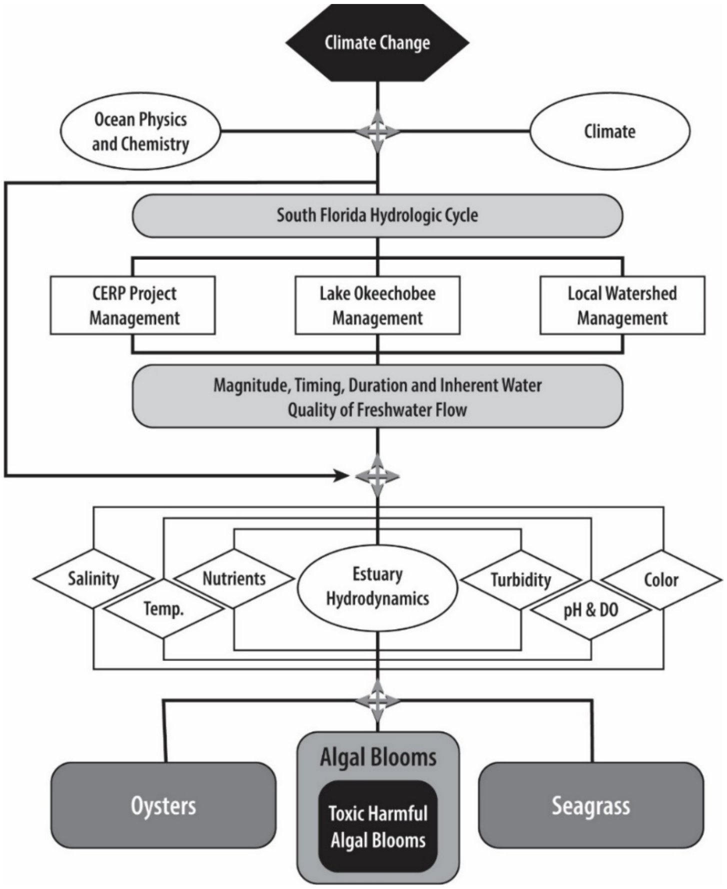

FIGURE 5-9 Simplified conceptual model of the northern estuary linkages between the CERP, Lake Okeechobee and local watershed land use and management, freshwater flows (and inherent water quality), estuary water quality and hydrodynamics, and significant environmental problems—HABs and climate change. Oyster and brackish and marine seagrass restoration represent CERP goals. Climate change can alter these fundamental environmental drivers.

shifting of nutrient loading toward larger loads during the dry season and smaller loads during the wet season, factors that could influence HABs.

Managers cannot begin to collectively understand system trade-offs and weigh difficult policy choices without a quantitative understanding of the interconnectivity of these environmental drivers and ecosystem problems and their linkage to regional water management (Box 5-3). Additionally, if the role of these different drivers is not better understood, CERP management may be criticized for adverse outcomes—for example, not meeting its goals for seagrass and oyster habitat restoration or harmful algal blooms—although these may be caused primarily by factors beyond the reach of the CERP.

Key Questions for Decision Makers on Restoration of the Northern Estuaries

All parts of the South Florida ecosystem—including the human and natural landscape—share a common water resource within a strongly interconnected hydrologic system. Human and natural ecosystem needs are synchronous and competing, exacerbated by the natural wet and dry cycles of Florida climate, the variability of which is further heightened by climate change (Graham et al., 2015). Therefore, water management decisions inevitably involve trade-offs and difficult policy decisions. Managers will need science to address critical questions such as those posed in Box 5-4 to better inform these decisions.

BOX 5-3 Water Management and Interconnected Environmental Drivers of Harmful Algal Blooms

Generally, the most successful strategies to mitigate marine and freshwater HABs in estuaries include reducing the supply of nutrients and restoring hydrologic regimes to promote mixing and destratification of the water column (Paerl et al., 2016). Control of both nitrogen (N) and phosphorus (P) is key. Given optimal temperatures and light, photosynthetic phytoplankton (e.g., *Karenia brevis*) and cyanobacterial biomass accumulation is directly proportional to the amount of nutrients (nitrogen and phosphorus) available in the water column (Paerl et al., 2016). At low and intermediate nutrient loadings, reduction in either nitrogen or phosphorus may be sufficient to control cyanobacterial blooms. However, under elevated loadings of both nitrogen and phosphorus, reduction of only one nutrient can result in an imbalance in the N:P ratio of the water column, potentially leading to a worsening of the cyanobacterial problem, or even lead to a eukaryotic (algal) HAB condition (Paerl, 2008; Paerl et al., 2011, 2014; Smith, 1983). Studies have shown that even when cyanobacterial blooms are phosphorus limited, elevated nitrogen can actually cause these blooms to become more toxic (Gobler et al., 2016; Kramer et al., 2018).

Water management decisions may affect algal blooms in the northern estuaries in complex ways. On the positive side, higher freshwater flows during the dry season are expected to decrease stratification and hydrologic residence times during the season when blooms are the most frequent. However, nutrient-rich waters held for extended periods within the C-43 and C-44 reservoirs could potentially seed blooms when released in the estuaries. Regulatory water releases from Lake Okeechobee can introduce cyanobacterial blooms into the St. Lucie and Caloosahatchee River Estuaries. These releases also contribute to elevated nutrients (Kramer et al., 2018; Lapointe et al., 2017; Rosen et al., 2018), which together may trigger or intensify blooms in downstream estuaries. Higher flows have been used as a management tool to flush blooms and cyanotoxins from the estuary before they have an opportunity to intensify, but such an approach also creates salinity conditions that are deleterious for oysters and seagrass, a key CERP outcome in the northern estuaries. Loss of seagrass, as a keystone habitat, could result in a highly turbid, phytoplankton-dominated estuary—an environment freshwater and marine HABs are able to exploit. This regime shift, which is already occurring in both estuaries, should be halted and factors affecting recovery trajectories need to be better understood.

BOX 5-4 Key Questions Relevant to the Northern Estuaries Management Decisions

1. **How can the operations of CERP storage and treatment projects and Lake Okeechobee be optimized to minimize HABs and maximize other ecological goals?**
    - What are the trade-offs between CERP goals, water quality objectives, and human water resources needs?
    - How does the timing of CERP and non-CERP restoration actions affect the delivery of benefits?
    - Do CERP reservoir operations seed HABs, and what operational adjustments can minimize those effects?

2. **How does water quality associated with freshwater flows affect CERP goals for restoration of seagrass and oyster habitat?**

3. **How can water management foster increased ecosystem resilience in light of climate change?**

Science Support for Restoration Management Decisions in the Northern Estuaries

Meeting the challenge of restoring the northern estuaries will require an advanced set of decision support tools—monitoring, research, syntheses, and modeling—in combination with effective coordination and communication among scientists and water quality and natural resource managers to collectively develop and implement these tools to support decision making. As the CERP moves from restoration planning to project execution, tools will be needed that can evaluate trade-offs in system operation between HABs, water quality,[5] seagrass and oyster restoration, and water supply under current and future conditions, considering system interconnectivity and nonlinear feedbacks. Such tools could be used to quantify understanding of management alternatives; they would support long-term regional planning and coordinated management actions among CERP, water quality, and natural resources managers. In this section, the status of science and readiness of observations, synthesis, and statistical and numerical modeling tools to meet this challenge are reviewed and key priorities for their incremental development are identified.

Integrated Hydrologic System Observations and Modeling

Basin-scale, watershed and estuarine hydrology observations and models have been well synchronized and validated for the northern estuaries over the past two decades. Models consist of (1) regional-scale "basin" models that predict flows based on current or natural system conditions using a hindcast of precipitation and climate data (e.g., 1965-2005), (2) finer-scale models of watershed (pollution) loading for water quality analyses or hydrologic models that optimize design and operations at the project scale, and (3) estuarine hydrodynamic models (Figure 5-10 and Table 5-5). Capabilities of these models to predict the influence of water management and land use on watershed freshwater flows to northern estuaries is generally high. A common set of estuarine hydrodynamic models has been validated against observations for water, salinity, and heat budgets (Ehlinger et al., 2019; FDEP, 2008; Ji et al., 2007; Qiu and Wan, 2013; SFWMD, 2018d; Tetra Tech, 2017) and used to assess water quality (FDEP, 2008; Tetra Tech, 2017) and minimum flow requirements (SFWMD, 2002, 2018d). Hydrologic basin models and estuarine hydrodynamic models have been a scientific workhorse for the CERP. They are used to predict the salinity ranges as a function of ocean forcing and prescribed freshwater flows, informing discussions on high-volume and low-flow targets needed to meet salinity performance measures (Ehlinger et al., 2019). Overall, the readiness of the integrated hydrologic system toolkit to serve as decision support for management of water flows into the northern estuaries is high and the explicit scientific needs in the short term are low.

Use of existing hydrologic models to predict the effects of climate change is a near-term high priority, considering the past and potential future effects of climate change on the South Florida ecosystem (NASEM 2016; NRC, 2014; SFWMD, 2009), and efforts have been relatively limited to date. The SFWMD published two reviews of the impacts of climate warming, drought, and sea-level rise on the hydrologic cycle and South Florida infrastructure (SFWMD, 2009, 2011), and researchers have conducted limited scenario analyses on the impacts of climate change and sea-level rise on the ecosystem (e.g., Flower et al., 2017; Koch et al., 2015; Obeysekera et al., 2015). NASEM (2016, 2018) outlined a broader approach to examine the implications of possible future climate scenarios, including changes in precipitation (e.g., average, seasonality, extremes), temperature, and sea-level rise on the South Florida ecosystem. A similar strategy was recommended by Graham et al. (2020), but such modeling analyses have not been conducted by CERP agencies. The SFWMD hydrologic models in current use are capable of predicting outcomes based on a range of potential precipitation and climate scenarios constructed from downscaled climate predictions.

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[5] Defined here as inclusive of temperature, salinity, turbidity, water color, nutrients (phosphorus, nitrogen), phytoplankton biomass, dissolved oxygen, and pH.

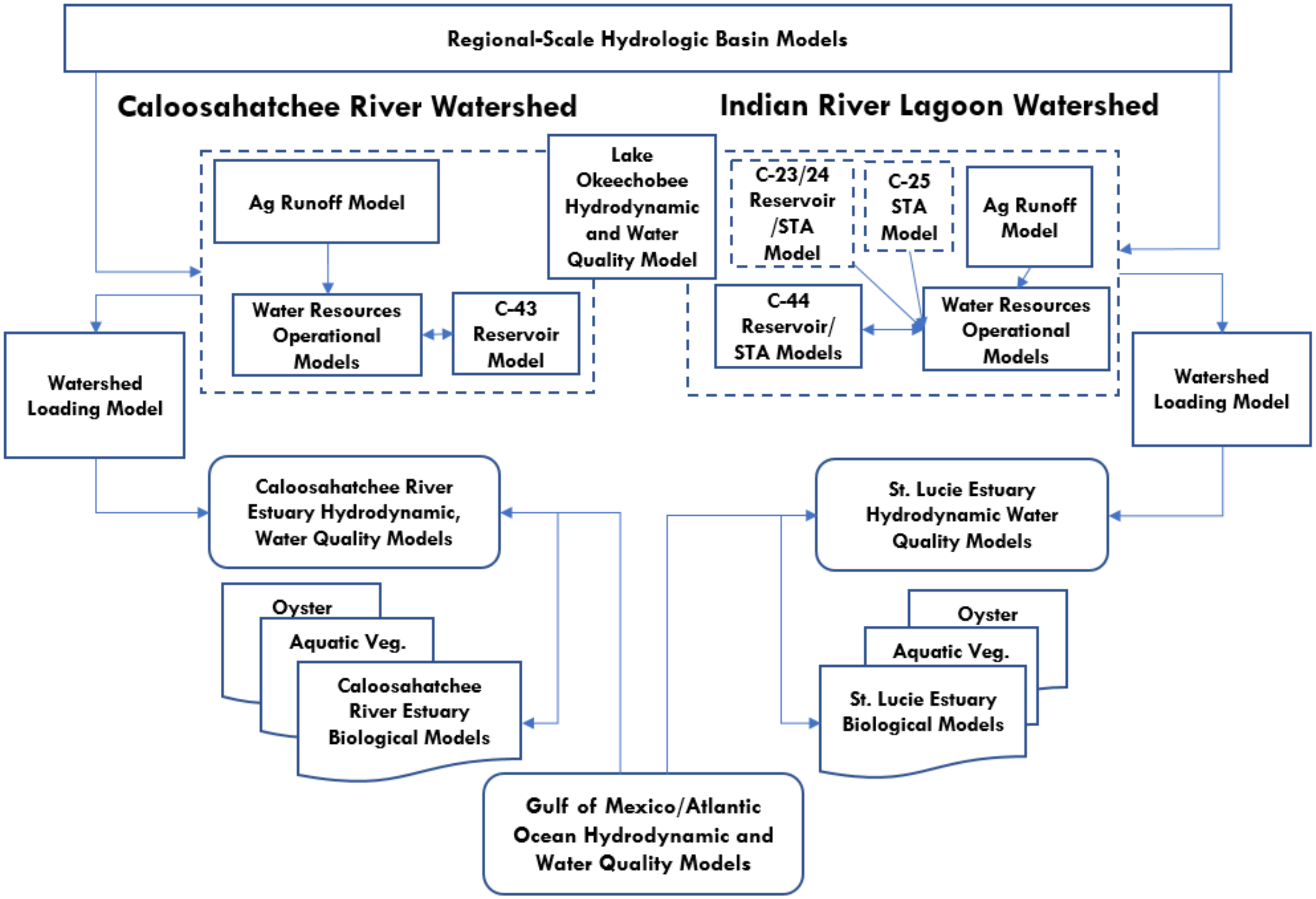

FIGURE 5-10 Conceptual illustration of the types of models that can be used to investigate restoration and water quality outcomes in the northern estuaries. The two estuaries share a regional-scale hydrologic basin model and Lake Okeechobee model. Other models are explicitly developed or configured for each individual estuary and its respective watersheds, including watershed loading and estuarine hydrodynamic, water quality, and biological models.

TABLE 5-5 Examples of Regional-Scale, Watershed and Estuary Hydrodynamic and Water Quality Models Applied to the Caloosahatchee River and St. Lucie Watersheds

Name	Description
Regional-scale hydrologic and water resources management models	
Regional Simulation Model (RSM) and Natural System RSM (NRSM)	The RSM simulates surface and groundwater hydrology for current or future (RSM) or predrainage (NSRSM) conditions in response to historic climate records and data. The model outputs water levels and flows from canals, water control structures, local topography and storage reservoirs, etc. It simulates the movement and distribution of water in conjunction with the coordinated operation of canals and structures (Bras et al., 2019; SFWMD, 2005).
South Florida Water Management Model (SFWMM)	Regional-scale operational model that simulates the major components of the hydrologic cycle in South Florida on a daily basis and analyzes operational changes to the water management system in South Florida (SFWMD, 2005).
Reservoir Optimization Model	Optimizes reservoir operations to meet the estuarine flow requirements and supplemental irrigation needs and provides day-to-day operational support for reservoirs and STAs in the watershed. Most recent version (OPTI7) used to determine optimal operating rules for detention reservoirs in the northern estuaries (Labadie, 2004).
Hydrodynamic and water quality models (lake, watershed, and estuary)	
Lake Okeechobee Water Quality Model	Simulates Lake Okeechobee water budget, temperature, CBOD, dissolved inorganic and organic nitrogen, phosphorus, phytoplankton biomass, cyanobacterial biomass, TSS (James, 2016)
Watershed Model (WaSH)	Hydrologic model; components are comprised of surface water flow, groundwater flow, channel flow, and water management practices (SFWMD, 2018d). Used in the CRE and STL; regions with high groundwater and dense array of drainage canals; this model is capable of simulating hydrology for such regions (SFWMD, 2018a).
Hydrological Simulation Program Fortran (HSPF)	Simulates CRE watershed DO, biochemical oxygen demand (BOD), temperature, TSS, sediment, ammonia (NH_3), nitrite-nitrate (NO_x), organic nitrogen (OrgN), orthophosphate (PO_4), organic phosphorus (OrgP), and phytoplankton (Tetra Tech, 2017).
Curvilinear Hydrodynamics in 3D (CH3D)	Time-varying 3D numerical hydrodynamic model used in both the CRE and STL. Coupling of the model with other modules (sediment transport and water quality) makes CH3D an integrated modeling system capable of simulating water quality and other estuarine processes (Sun et al., 2016; Wan et al., 2012).
Environmental Fluid Dynamics Code (EFDC)	An EPA-sponsored 3D hydrodynamic and water quality model that transports salinity, temperature, simple constituents (e.g., tracer), sediments, and toxic contaminants (e.g., metals or organics; Tetra Tech, 2017).
Ecological models	
Oyster, Habitat Suitability Index	Calculates habitat suitability for larval and adult oysters as a function of salinity, temperature, flow for larvae, and substrate for adults in the CRE (Barnes et al., 2007).
Oyster, Mechanistic	Predicts adult oyster survival related to freshwater inflows and salinity in the CRE. Model incorporates filtration rate, assimilarion efficiency, mortality, and TSS, salinity, and temperature effects (Buzzelli et al., 2013b). In the STL, predicts oyster biomass production and filtration related to salinity, freshwater flow. Model incorporates temperature and TSS and impacts of oyster clearance on phytoplankton biomass (Buzzelli et al., 2013a).

(Continued)

TABLE 5-5 Continued

Name	**Description**
Ecological models	
Seagrass, Mechanistic	Process-based model to examine the effects of temperature, salinity, and light attenuation (chlorophyll a, color, turbidity) on *Vallisneria* survival and biomass in CRE relating survival and mortality to salinity and freshwater flow (SFWMD, 2018a, Appendix A).
	CRE process-based model that predicts seagrass survival for *T. Testidinum and H. wrightii* as related to freshwater flow, nutrient loading, and light attenuation (turbidity, color, chlorophyll a) with gross primary production, respiration, mortality, and translocation modulated as functions of water temperature, depth, and light availability (Buzzelli et al., 2014b).
	Process-based model that predicts seagrass *S. filiforme* biomass via mortality, respiration, and gross primary production as a function of salinity, water depth, water temperature, and light attenuation in the STL (Buzzelli et al., 2012).

NOTE: BOD, biochemical oxygen demand; CBOD, carbonaceous biochemical oxygen demand; CRE, Caloosahatchee River Estuary; DO, dissolved oxygen; HYD, hydrodynamic; STL, St. Lucie Estuary; TSS, total suspended solids; WQ, water quality.

Watershed Loading and Estuarine Water Quality and HAB Toolkit

As the CERP is implemented, CERP project and Lake Okeechobee operations will need to be refined to maximize CERP goals, minimize HABs, and balance trade-offs between restoration objectives and human water resources needs (see Box 5-5). However, RECOVER (2020) notes that current CERP performance measures are not designed to address water quality or HABs and any future evaluation and assessment of water quality performance measures would require "predictive modeling tools not available at this time." To confront this management challenge, observations, syntheses, and models are needed that address two major lines of investigation. First, it is necessary to quantify how cyanobacterial blooms are linked to flow and the degree to which Lake Okeechobee and future operations of the reservoirs/STAs are seeding downstream HAB events in the northern estuaries (Graham et al., 2020). Beyond flow, other site-specific conditions will favor or disfavor cyanobacterial or marine HABs and their toxic events, many of which are linked to climate change (e.g., nutrient species, carbon dioxide concentrations, temperature). The second line of investigation is the linkage of flow/salinity and water quality (turbidity, CDOM, nutrients, algal blooms) to light limitation for seagrass. These causal mechanisms need to be investigated comprehensively through observations, syntheses, and models—from Lake Okeechobee, the CERP reservoirs, and STAs (see Box 5-3) to the local watersheds and the northern estuaries themselves.

The scientific toolkit to support these investigations of environmental drivers of water quality in the northern estuaries and their impacts on HABs consists of observations, synthesis, and predictive models. Watershed exports can be represented by observations or watershed loading models that predict surface flows and constituent loading from local contributing basins. The computed watershed loads are currently integrated with water releases from Lake Okeechobee and could be linked with detailed measurements and models on water releases from reservoirs, and STAs as they come online. Watershed loading models provide inputs to coupled estuarine hydrodynamic and water quality models (Figure 5-10). These estuarine water quality models produce spatially explicit predictions of mass balances of oxygen, inorganic and organic nutrients, and organic carbon. These in turn are associated with "compartments" of lower trophic level ecosystem models (e.g., freely dissolved or associated in the live or dead biomass of primary producers and consumers). Ocean observations or models provide forcing of hydrodynamics and water quality to represent exchanges with the ocean.

In this section, the status of the existing scientific toolkit (including observations, synthesis, and predictive models) to support these decisions linked to water quality in the northern estuaries and their contributing basins is discussed.

Status of water quality and HAB observations. Florida has a long history of investing in water quality monitoring, supported by active local partnerships (Patino, 2014). As with many states, Florida's HAB monitoring appears to be focused on HAB event response and routine monitoring to assess risk to human health, recreation, and drinking water[6] (i.e., public health advisories). Many environmental drivers are routinely monitored (flow, nutrients, temperature) or could be derived from water quality model output, but they are not currently synchronized in time and space with inland HAB monitoring. Adding HAB response indicators to routine water quality stations may address this gap. A monitoring program has recently been reinvigorated to investigate the environmental drivers of phytoplankton community composition and harmful algal bloom species in the St. Lucie Estuary (A. Wachnicka, SFWMD, personal communication, 2020), as an example of improved monitoring. A similar program was also proposed but listed as unfunded in the Caloosahatchee River Estuary (SFWMD, 2019). Remote sensing federal–state collaborations, such as the Cyanobacteria Assessment Network (CyAN; Coffer et al., 2020; Urquhart et al., 2017), offer historical data that could be used for analyses and modeling hindcasts or real-time or seasonal forecasting. These could support operation of the control structures in a manner that allows both water quality and quantity to be considered in adaptive management.

Predicting watershed and estuarine water quality. Watershed loading and estuarine water quality models are routinely applied to manage nutrients and eutrophication in estuaries. State

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[6] See https://fdep.maps.arcgis.com/apps/webappviewer/index.html?id=d62c3487e8de49f6b3a6559cdf059e14.

investments have supported the development of a series of watershed and estuarine water quality models for the St. Lucie and Caloosahatchee basins (Buzzelli et al., 2014b,c; Tetra Tech, 2017). These tools were developed to support management decisions on nitrogen and phosphorus TMDLs and basin management action plans (BMAPs). As CERP projects affecting the northern estuaries are completed and come online, these modeling tools can help decision makers understand the effects of these projects and Lake Okeechobee operations on water quality. Water quality parameters (e.g., temperature, salinity, nutrients, turbidity, water color, phytoplankton and benthic algal biomass, dissolved oxygen) are linked to HABs (Burford et al., 2020) and are important predictors of habitat condition for oysters and seagrass (Buzzelli et al., 2013a, 2014c).

In the Caloosahatchee River Estuary and watershed, the quantitative understanding of water quality drivers is more comprehensive than in the St. Lucie Estuary. Buzzelli et al. (2014b,c) developed a box modeling approach to estimate the relative effects of water color, chlorophyll a (an indicator of algal growth), and turbidity on light availability to seagrass. A watershed loading and estuarine hydrodynamic and water quality model has recently been updated and calibrated to support refinements of the TMDLs for the estuary (Tetra Tech, 2017). Watershed nutrient and suspended sediment loads by sources and pathways have also been updated along with improvements in predictions of estuarine nutrient concentrations, dissolved oxygen, and chlorophyll a (Tetra Tech, 2017). Although these models may be sufficient to inform decisions on a revised nitrogen TMDL, application of this specific version to investigate site-specific controls on HABs or optimize CERP seagrass restoration may be limited, unless additional improvements are made. First the watershed loading model overpredicted turbidity and did not specifically predict dissolved organic carbon, which was used in the estuary water quality model as a proxy for CDOM. Moreover, the estuary water quality calibration revealed challenges with the accuracy in spatial predictions of chlorophyll a, turbidity, and dissolved organic carbon, all of which impact light attenuation—a key control on cyanobacteria dominance and seagrass habitat quality (Tetra Tech, 2017). Additional process studies are needed to tune model constants to refine the watershed loading and estuarine water quality model calibration. Monitoring and research are currently under way at the SFWMD to better understand the sources and gradients of turbidity and CDOM in both the Caloosahatchee and the St. Lucie watersheds and to evaluate how this could improve water quality predictions in the estuary.

In contrast, comprehensive synthesis and modeling to predict watershed loading and estuarine water quality in the St. Lucie Estuary is lagging behind that of the Caloosahatchee, although extensive monitoring data exist. Limited synthesis and modeling constrains the ability to predict the water quality factors affecting HABs or suitable habitat for seagrass and oysters. The most recent hydrodynamic and water quality modeling effort occurred to support the nitrogen and phosphorus BMAP of the St. Lucie Estuary (Ji et al., 2007; SFWMD, 2018d; Wan et al., 2012), which specified the implementation plan to achieve the 2008 nitrogen and phosphorus TMDLs. Wan et al. (2012) noted issues with water quality model calibration (e.g., bias, low model skill) specifically with respect to nutrients, phytoplankton biomass, and dissolved oxygen. Turbidity and CDOM were not modeled, even though these parameters are known to play an important role in controlling primary production, respiration, and light limitation for seagrass. A watershed loading model for the St. Lucie Basin has been recently recalibrated, but the authors noted issues with spatially resolved predictions of inorganic and organic nitrogen and chlorophyll a. Again, CDOM and turbidity were not specifically simulated (SFWMD, 2018d).

Predicting HABs. Although water quality modeling is in routine practice, understanding the mechanisms of HABs and predicting blooms from waterbody hydrodynamics and water quality is still an emerging and rapidly evolving area of science (Burford et al., 2020; Stauffer et al., 2019). Hindcasts and seasonal forecasting based on proxies of cyanobacterial biomass are most advanced for well-studied waterbodies (e.g., Lake Erie; Bridgeman et al., 2013; Obenour et al., 2014; Stumpf et al., 2012), but the science of prediction of toxic events at a whole-waterbody scale is in its infancy (Burford et al., 2020). Incremental steps are useful; empirical models can be used to refine regional or waterbody-specific risk relationships based on the probability of increasing toxic bloom events with increased chlorophyll a, nitrogen, and phosphorus (Yuan and Pollard, 2015; Yuan et al., 2014) or to support short-term forecasts of cyanobacterial blooms (Wynne et al., 2013). Building a predictive HAB modeling toolkit for the northern estuaries requires implementation of a sustained long-term monitoring and research program in both northern estuaries and their contributing basins, including CERP projects. This predictive toolkit would need to comprehensively link environmental drivers (e.g. nutrients, meteorological and hydrologic conditions) to eutrophication and HAB responses, such as remotely sensed phycocyanin (a pigment in cyanobacteria) and chlorophyll a, *in situ* phytoplankton community composition, cell counts, and toxin concentrations. These investments would help to identify environmental drivers of toxic HAB events and effective approaches for their mitigation.

Incremental progress has been made predicting HABs in Lake Okeechobee. The Lake Okeechobee Water Quality Model has been developed to predict eutrophication and cyanobacterial blooms. James (2016) described results modeled over the period 1983-2012 as excellent for inorganic suspended solids, light extinction, total phosphorus, and dissolved inorganic phosphorus, but the model did not meet goodness-of-fit criteria for total nitrogen, dissolved inorganic nitrogen, chlorophyll a, and relative abundance of cyanobacteria versus other phytoplankton functional groups. James (2016) noted that process studies are needed to represent more complex representation of the full nitrogen cycle and algal (including HAB) community responses to nutrients, their variable carbon-to-nitrogen ratios, and other environmental factors.

Water quality and HAB modeling is also needed for CERP projects. This is particularly true for the C-43 and C-44 reservoirs, which are expected to hold water for extended release during the dry season, when temperatures are highest and thermal stratification could expect to set up ideal conditions for cyanobacterial blooms. C-44 is being planned to incorporate an STA, but their ability to reduce nitrogen concentrations or remove cyanobacterial cells or associated toxins is not well quantified (see also Chapter 3). Because management of cyanobacterial blooms requires management of both nitrogen and phosphorus (Gobler et al., 2016; Kramer et al., 2018), research on nitrogen cycling and its role in cyanobacterial blooms is needed to complement the long history of phosphorus research in the northern Everglades.

Climate change is already exacerbating conditions that support HABs (e.g., higher temperature, thermal stratification, drought and associated low flows and long residence time, high irradiance, high carbon dioxide concentrations; Burford et al., 2020). Given these pressures on water management, it will be essential to understand the system interconnectivity and feedbacks to be able to specify the precise environmental flow requirements of the northern estuaries, understand the trade-offs between flow, water quality, and HABS, and determine how water quality management (source reduction, treatment versus ecosystem restoration) can improve ecosystem resilience. Florida's capacity to respond to these climate change pressures will be aided by a water quality and HAB decision support toolkit, with investments to make models increasingly mechanistic (Burford et al., 2020).

Ultimately, understanding the expected and actual effects of CERP investments on water quality and the changing trends outside of CERP management that affect estuary water quality will be essential to inform ongoing decisions about operations and the need for investments to meet CERP and non-CERP estuary restoration goals. The scientific priority is high because of the risk of CERP not meeting its goal, not to mention the risk of HAB effects on human and ecosystem health and the Florida economy. It is beyond the scope of this report to address the full list of science questions needed to inform HAB management; Florida's Blue-Green Algae Task Force is beginning to address these issues.[7] Nevertheless, silos between CERP and non-CERP efforts will only hinder progress on this issue. CERP planners need to understand the evolving science on HABs and adapt planning and operations to this understanding.

Biological Effects Monitoring, Synthesis, and Modeling

As CERP planning proceeds, decision makers will need to understand how Lake Okeechobee and CERP reservoirs/STAs can be operated to achieve seagrass and oyster goals, while minimizing HABs. As

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[7] See https://protectingfloridatogether.gov/state-action/blue-green-algae-task-force.

Eastern Oyster
(*Crassostrea virginica*)
Mesohaline/Marine bivalve

Shoal Grass
(*Halodule wrightii*)
Mesohaline/Marine SAV

Tape Grass
(*Vallisneria americana*)
Freshwater/Oligohaline SAV

FIGURE 5-11 Species that are used as CERP biological endpoints that are impacted by the magnitude, timing, and water quality of freshwater flows to the northern estuaries. SOURCES: FWS (2017), Hans Hillewaert/Wikimedia Commons, and https://www.nps.gov/foma/learn/nature/images/Oyster-Reef.JPG?maxwidth=650&autorotate=false.

noted in the previous section, trade-offs are likely and need to be spatially quantified. Flow and salinity are also linked to management of stressors associated with climate change (e.g., sea-level rise, increased flood and drought, increased ocean acidification, temperature, HABs). To quantify these trade-offs and manage these estuaries toward improved ecosystem resilience, the CERP needs biological modeling tools that can capture the quantitative, nonlinear relationships among freshwater flows, interconnected estuarine environmental drivers, and these major biological outcomes.

Recently updated RECOVER salinity and hydrologic performance measures have been developed using estuarine numerical hydrodynamic models to establish spatially explicit flows associated with salinity ranges that are considered “optimal” for Eastern oyster (*Crassostrea virginica*), brackish-water, and marine seagrass (RECOVER, 2020; Figure 5-11). The “optimal” salinity ranges were established based on experimental and field-based studies and long-term monitoring data of organismal responses to changes in salinity. This “conceptual habitat area approach” was used to query model simulations over a 50-year period in order to produce the flow envelopes that represent the maximum potential habitat for each indicator species (RECOVER, 2020). RECOVER used these revised performance measures combined with recently updated and quantitatively validated habitat suitability index (HSI) models for its analysis of Interim Goals (due in late 2020); the Interim Goals and these updated biological models were not available for review by the committee. Previously published examples of HSI models for seagrass and oysters are empirical representations of the relationships between environmental drivers (e.g., salinity) and organism responses (seagrass extent).

These empirical models are useful as restoration planning tools, but RECOVER (2020) acknowledges that this simplified modeling approach, which represents the “best available science,” is insufficient to optimize flow regimes for several reasons. First and most importantly, the RECOVER (2020) conceptual habitat approach relies primarily on salinity to define potential habitat, when other factors (e.g., light availability, CDOM, nutrients, chlorophyll a, turbidity, food resources, temperature) can exert strong controls. Empirically derived HSIs, although useful for many applications, do not capture the nonlinear feedbacks that occur when organisms are exposed to multiple stressors or resources that vary over time and space (Livingston et al., 2000). Second, both the conceptual habitat approach and any empirically derived HSI average over ecologically important time steps. For example, flow–salinity relationships were analyzed based on 2-week means (RECOVER, 2020), but extreme precipitation events can have deleterious effects on oysters and seagrass on short-term timescales of days to weeks. Third, mechanistic physiologically based models are likely to provide better predictions than empirical models for atypical combinations of drivers (e.g., sea-level rise, acidification, warming). Thus, the readiness of this biological toolkit to optimize flows for seagrass and oysters and inform management decisions that foster ecosystem resilience in light of climate change is moderate for reasons explained in detail below.

The scientific priority is high, because this is a key limitation for CERP to reach their goals and to provide clear justification for how HABs and water quality issues can be minimized, while optimizing CERP seagrass and oyster restoration goals.

Ideally, estuarine biological tools to optimize seagrass and oyster habitat would be species-specific, spatially explicit mechanistic models that depict physiological responses to highly variable temporal and spatial gradients in flow and water quality parameters (e.g., salinity, temperature, turbidity, substrate, nutrients, CDOM, phytoplankton biomass). They would be driven by output from or dynamically coupled to estuarine hydrodynamic and water quality models to predict spatially explicit biological outcomes (e.g., seagrass biomass). Because they are mechanistic and physiologically based, these biological models can ultimately be used to evaluate trade-offs and refine restoration and adaptive management strategies as these estuaries evolve with climate change. Process-based physiological seagrass unit-modeling approaches are well established that predict above- and belowground biomass as a function of physiological stressors (salinity, temperature, root oxygen, light limitation) and resources (nutrients, carbon) (Madden, 2013; Madden and McDonald, 2010). Approaches for process-based, mechanistic oyster models are also well established (Dekshenieks et al., 2000; Fulford et al., 2007; Powell et al., 2003; Wang et al., 2008), in which oyster filtration and growth are linked to environmental conditions and food resources, including incorporation of feedback relationships (e.g., effects of oyster biodeposits on nutrient cycling; Cerco and Noel, 2007).

Important assets exist in South Florida with which to construct these more advanced biological modeling tools. The SFWMD invested in two decades of oyster and seagrass monitoring and research within the northern estuaries. Comprehensive conceptual models have been published for the Caloosahatchee River Estuary (Barnes, 2005) and the St. Lucie Estuary (Sime, 2005) and relationships among drivers are generally understood. The SFWMD has also been working to incrementally advance syntheses and empirical and process-based models with relationships to flow and salinity, based on these monitoring data for the northern estuaries.

The Minimum Flow and Minimum Water Level 2018 update for the Caloosahatchee River Estuary is the most recent and comprehensive example of a synthesis and model development across multiple biological endpoints. Mechanistic or statistical models for 11 different estuarine biological response endpoints were developed to identify minimum flow targets. SFWMD (2018a) noted that the existing monitoring data posed significant challenges to developing empirical relationships with flow and salinity, because of changes in seagrass and oyster monitoring protocols in the mid-2000s. As of 2018, RECOVER and SFWMD reinstated an improved, intensive seagrass monitoring program in both of the northern estuaries, using more appropriate standard methods that are responsive to changing environmental conditions (e.g., Neckles et al., 2012), with greater spatial resolution (RECOVER, 2020; SFWMD, 2019). These are positive changes that will improve the value of the monitoring data collected, although prioritizing observations and research specifically to inform iterative mechanistic model development would expedite the development of tools to support CERP decision making.

Although no comprehensive synthesis of flow relationships with various biological endpoints has been completed for the St. Lucie Estuary (SFWMD, 2000), observations and research have been harnessed to develop seagrass and oyster process-based models for both estuaries (Table 5-5; Buzzelli, 2011; Buzzelli et al., 2012, 2013a, 2014b). These models represent an incremental step toward an advanced biological toolkit. For example, the process-based oyster model for the St. Lucie Estuary (Buzzelli et al., 2013a) could give a spatially resolved estimate of potential habitat acreage and also inform the higher level of nutrient loading tolerated if oyster restoration goals were achieved. For seagrass, agency expertise exists to develop a more mechanistic, process-based approach for the St. Lucie Estuary, similar to that already in application in Florida Bay (Madden, 2013; Madden and McDonald, 2010). These modeling efforts could take advantage of improved seagrass monitoring by the SFWMD now under way as well as recent advances in water quality modeling to develop more spatially explicit predictions of seagrass biomass and distribution. Although freshwater flow will exert a major control on seagrass distribution, localized influences such as shoreline development, multiple uses (e.g., marinas, boating), and pollutant inputs may apply important controls on what oyster and seagrass habitat can be recovered locally.

This mechanistic, spatially explicit biological toolkit can provide important decision support to formulate a management strategy to respond to climate change. Rising sea levels will increase salinity levels in the northern estuaries and compress estuarine habitat. Acidifying and warming habitat will further stress all estuarine biota, including seagrass and oysters. Consideration should be given to incorporation of climate change stressors into the current monitoring and modeling program in order to build capacity for predictive modeling that can be used to optimize ecosystem resilience.

TABLE 5-6 Criteria and Status of Monitoring, Research, Syntheses and Predictive Modeling Tools for the Northern Estuaries

Category	Criteria for Status of Scientific Components	Status	
		Caloosahatchee	**St. Lucie**
Integrated Hydrologic System	**Terrestrial hydrologic basin predictions**: Can capture links in the hydrologic cycle from northern everglades, WCAs, STAs, and water resource operations (including impacts of climate change)	Advanced	Advanced
	Coupled freshwater–groundwater predications to estuaries and estuary hydrodynamic models: Freshwater flows from surface and groundwater, ocean tidal forcing and WSE (water surface elevation), estuarine hydrodynamic water, salinity (including impacts on climate change)	Advanced	Advanced
Watershed and Estuarine Water Quality	**Can predict watershed water quality** including the temporal variability in water quality in releases of water from Lake Okeechobee, CERP projects as they come online (C-43, C-44 reservoirs, STAs), and local land uses as a function of external and internal drivers	Intermediate	Early Stage
	Can predict estuarine water quality, including the ability to estimate/model patterns in concentrations and mass balances of nutrients and organic carbon, production of algae and partitioning among major taxonomic groups, and the factors limiting light to seagrass. Models should be spatially and temporally resolved to investigate management options at a local scale.	Intermediate	Early Stage
	Can predict watershed and estuarine toxic HABs as a function of environmental drivers. Simple statistical or empirical models can quantify risk relationships based on observations, while building toward mechanistic models and operational models that could be used to remediate drivers or develop rapid response management actions in response to bloom events	Emerging	Emerging
Biological Outcomes	**Can predict seagrass biomass:** Spatially explicit, mechanistic biomass models would be used to predict restored habitat acreage as a function of flow regime and target and remediate local stressors within estuarine sub-basins. Modeled biomass would respond to changes in salinity and light regimes (linked to substrate, depth, and water quality, i.e., color, turbidity, and algal abundance/nutrients)	Emerging	Emerging
	Can predict spatially explicit estimates of oyster density: Based on estuarine volume, phytoplankton turnover (as a food resource), and oyster filtration rates. Water quality models (see above) could be used to provide inputs representing phytoplankton/detrital food resources for these process-based oyster models.	Intermediate	Intermediate

NOTES: Status ranges from *emerging* (observation or science components not yet implemented to capture relationships between drivers and environmental problems), *early stage* (basic relationships observed and reported but data gaps inhibit formulation of advanced predictive tools have not yet been addressed), *intermediate* (observations and research synthesized and preliminary predictive tools developed, more developments/refinements are needed), and *advanced* (predictive tools validated and in routine use). CRE, Caloosahatchee River Estuary; STL, St. Lucie Estuary.

Summary: Integrated Decision Support Tools for the Northern Estuaries

Meeting the challenge of restoring the northern estuaries will require an advanced set of decision support tools, in combination with effective coordination and communication among scientists, water quality managers, and natural resource managers (local, state, and federal), to collectively develop, implement, and integrate these tools. These tools, namely monitoring and research, syntheses, and modeling, could be used to support quantitative understanding of trade-offs, operationalize decisions, and support long-term regional planning and coordinated management actions among CERP and other water quality and natural resources managers to enable rapid response to changing conditions under future climate change. The criteria for and status of this northern estuary decision support toolkit are summarized in Table 5-6.

SOUTHERN ESTUARIES

The southern estuaries are part of a contiguous network of coastal wetlands and estuaries that extend from Biscayne Bay through Florida Bay to the Ten Thousand Islands on the southwest coast. The high habitat diversity of the region provides many benefits including support for a broad array of aquatic life, making the region one of the most ecologically and economically important in Florida (Graham et al., 2020; Sklar et al., 2005). Biscayne Bay and Florida Bay are the largest water bodies of the southern coastal system, and the CERP envisioned a series of restoration projects to improve the quantity and distribution of their inflows. In this section, the committee describes the hydrologic and water quality changes to these ecosystems, their ecological impacts, and restoration goals for Florida Bay and Biscayne Bay. In light of continued project planning and adaptive management in this region, key decisions for water management are discussed along with the adequacy of science to support these decisions.

Biscayne Bay

Biscayne Bay (Figure 5-12) is a highly productive and biodiverse tropical marine ecosystem consisting of a series of connected, shallow lagoons, many of which open to the Atlantic Ocean. Historically, large oyster beds occurred in the nearshore zone, and water was clear with seagrass reported at water depths of 10-12 feet. Until recently, Biscayne Bay supported vast benthic communities dominated by meadows of seagrasses (e.g., *Thalassia testudinum* and *Halodule wrightii*), which contributed to its value as nursery habitat and ultimately the function and dynamics of the larger Florida Keys coral reef ecosystem (Ault et al., 2001). Biscayne Bay supports a large coral reef environment and a diversity of species, including an estimated 150 species of shrimp, crabs, sponges, and lobsters and more than 500 tropical and temperate fish species. Manatees, dolphins, alligator, and crocodiles are present, and the coastal zone and intertidal areas are a major stopover for migrating shorebirds. In an effort to protect the Bay and its diversity, an area of approximately 270 mi^2 in central and southern Biscayne Bay was designated as Biscayne Bay National Park in 1982—the largest marine park in the U.S. national park system. The park protects one of the most extensive coral reef tracts in the world (Briceño and Boyer, 2011).

As a result of this diversity of habitats and species, Biscayne Bay provides a suite of ecosystem services including support of fisheries for food and recreation, protection from storms and flooding, water supply, climate regulation through carbon uptake and storage, and aesthetics (Armistead et al., 2019). These services are the basis for widespread economic activity that the citizens of Florida depend on, with the value of Biscayne Bay ecosystem services estimated to be between $1.5 and $2.2 billion annually (Armistead et al., 2019).

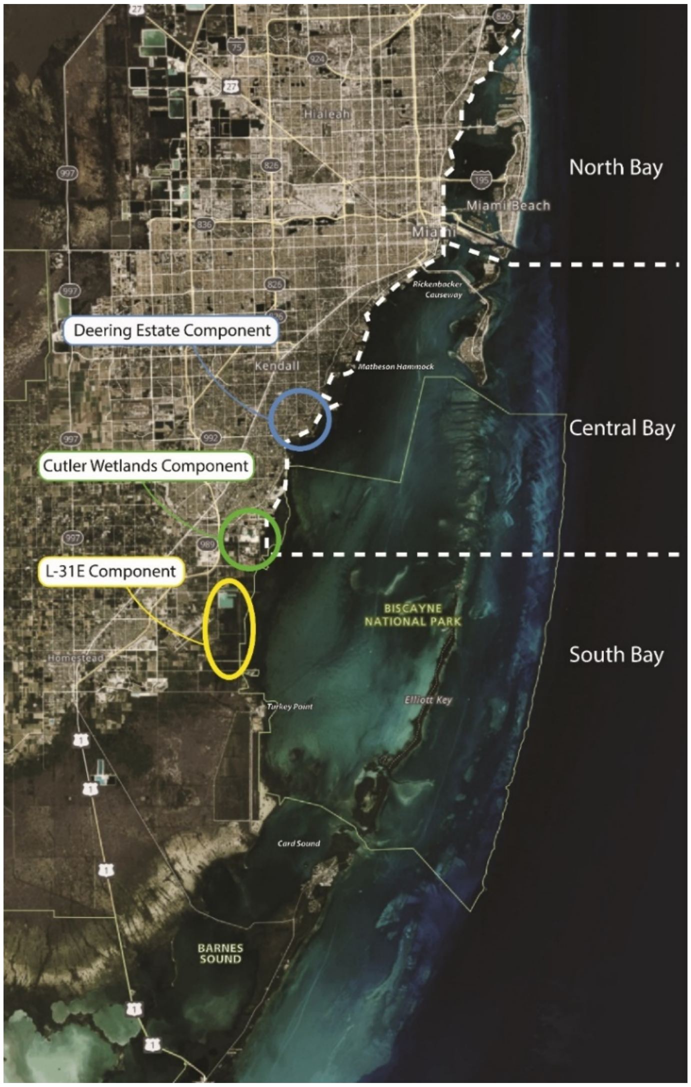

FIGURE 5-12 Map of Biscayne Bay showing the boundary of Biscayne National Park. SOURCE: Google Maps.

A gradient of conditions exists from north to south along the length of the Bay. To reflect these differences, Biscayne Bay is divided into three sections: the North Bay, which is bordered by the Miami urban area (from Dumfoundling Bay south to the Rickenbacker Causeway); South Biscayne Bay, with its watershed dominated by agricultural land use (from Black Point south to Barnes Sound); and the Central Bay, a transition zone between the North and South Bays (Caccia and Boyer, 2005; SFWMD, 1995). Recent declines in water quality in North and Central Biscayne Bay have caused massive seagrass die-offs (Millette et al., 2019; RECOVER, 2019), threatening the ecological condition of the Bay and complicating the opportunities for restoration under the CERP. The following sections detail the changing characteristics of Biscayne Bay, CERP objectives, and the status of existing science and modeling tools to guide restoration decision making.

Environmental Changes and Their Ecological Effects

Structural and hydrologic changes. Historically, Biscayne Bay was a tidal estuary that received surface water flows over and through the Atlantic Coastal Ridge from the Everglades (Lodge, 2017).

Sheet flows across coastal marshes and through numerous tidal creeks created an estuarine salinity regime of ~5-18 PSU in the fringing mangroves, tidal creeks, and the open water of the Bay (Kohout and Kolipinski, 1967; Lodge, 2017). Groundwater inflow from the Biscayne Aquifer was vital in support the biological diversity of the Bay (Kohout and Kolipinski, 1967). Much of the groundwater inflow entered the Bay from below, causing freshwater and saltwater to mix from the bottom up, limiting the water column stratification that is common in many estuaries (Lodge, 2017). Construction of the Central and South Florida Project and other drainage projects for flood control reduced groundwater levels and shifted the groundwater divide westward from the coastal ridge into Everglades National Park (Fennema et al., 1994). Surface and groundwater inflows were radically altered so that canal discharges and marine inflows now dominate (Wang et al., 2003); estimates are that groundwater inflows and overland flows currently represent just 10 and 6 percent of the total freshwater inflows, respectively (Briceño et al., 2011).[8] The decreases in groundwater flows have resulted in a transition of Biscayne Bay from an estuary to a marine lagoon (Lodge, 2017; Wingard et al., 2004), with high and variable salinity and periodic mesohaline conditions (5-18 PSU) in areas directly adjacent to the western shoreline that receive some freshwater inputs (Briceño et al., 2011). Salinities in the coastal wetlands have increased from 0 to 10 parts per thousand (ppt) under predrainage conditions to around 8-18 ppt at present (Gaiser and Ross, 2004). Urban development has also reduced and fragmented coastal habitats as the population of Miami-Dade County has grown from 12,000 people in 1910 to 2.5 million people in 2010.[9]

Biscayne Bay is now a fully marine system and the impacts of climate change and accelerating rates of sea-level rise are a major concern. Over the 31 years from 1985 to 2016, sea levels have risen by 6 inches at Miami,[10] while under USACE high sea-level rise projections, it may take only 15 years to rise by another 6 inches.[11] The impacts of sea-level rise in Biscayne Bay are many, including increased flooding and saltwater intrusion into freshwater canals and the Biscayne Aquifer. In response, Miami has expanded its stormwater pumping system that moves water from the city into the North Bay, carrying with it debris, sediment, and other pollutants.

Water quality. Nutrient enrichment in Biscayne Bay compounds the effects of altered hydrology. Historically, low phosphorus concentrations in flows from the Everglades resulted in a severe phosphorus limitation in the Bay's waters (Brand et al., 1991), but concentrations of phosphorus and chlorophyll a—an indicator of algal abundance—are increasing throughout the Bay (Caccia and Boyer, 2005; Millette et al., 2019; SFWMD, 1995). Over a 20-year period, from 1995 to 2014, chlorophyll a concentrations increased significantly in all three regions of Biscayne Bay, with the largest increase occurring in the North Bay (Figure 5-13; Millette et al., 2019). Currently, increases in both phosphorus and chlorophyll a are highest in the North Bay, which is highly urbanized with restricted circulation and high population density, and in nearshore stations in the Central Bay that are close to specific canal outflows (Brand et al., 1991; Briceño et al., 2011; DERM, 2019; Gimenez, 2019; Millette et al., 2019). Sources of phosphorus include untreated urban stormwater runoff, septic tank leachate, and runoff from agricultural land (DERM, 2019). Higher groundwater levels resulting from sea-level rise are a particular threat to the function of septic tanks; by 2018, an estimated 56 percent of septic tanks in Miami-Dade County (or more than 58,000 properties with septic tanks) were compromised during storms or wet years (Miami-Dade Circuit Court, 2018), leading to nutrient inputs and high fecal coliform levels in the North Bay.[12] FDEP recently verified Biscayne Bay as impaired by nutrients and high chlorophyll a levels, and a TMDL is planned. In support of this effort, specific nutrient criteria for the different sections of the Bay have been developed (Figure 5-13; Florida Administrative Code Rule 62-302.532).

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[8] This water budget is based on inflows south of the Rickenbacker Causeway. The remainder of the freshwater budget is canal flow (44 percent) and rainfall (40 percent).

[9] See http://www.census.gov/popest/data/index.html.

[10] NOAA, Station Data Virginia Key; see tidesandcurrents.noaa.gov.

[11] See www.corpsclimate.us.

[12] See https://floridadep.gov/dear/water-quality-restoration/content/impaired-waters-tmdls-and-basin-management-action-plans.

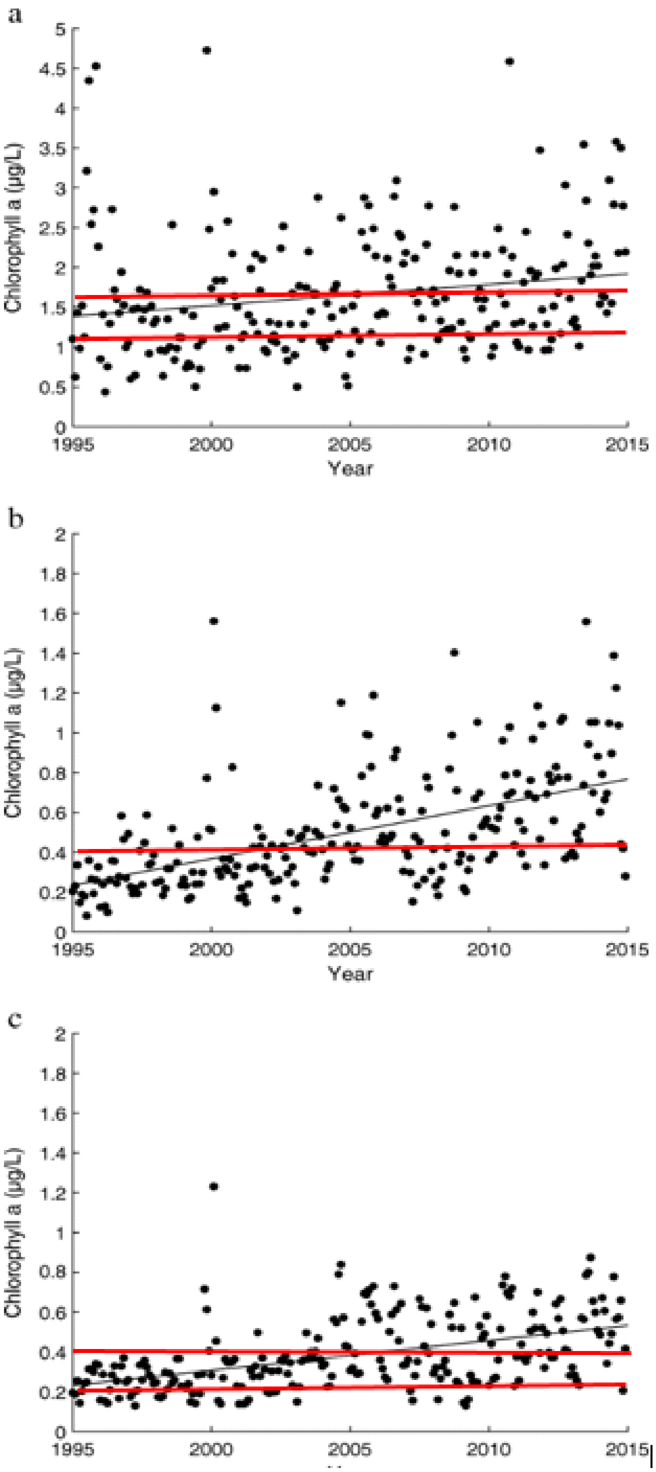
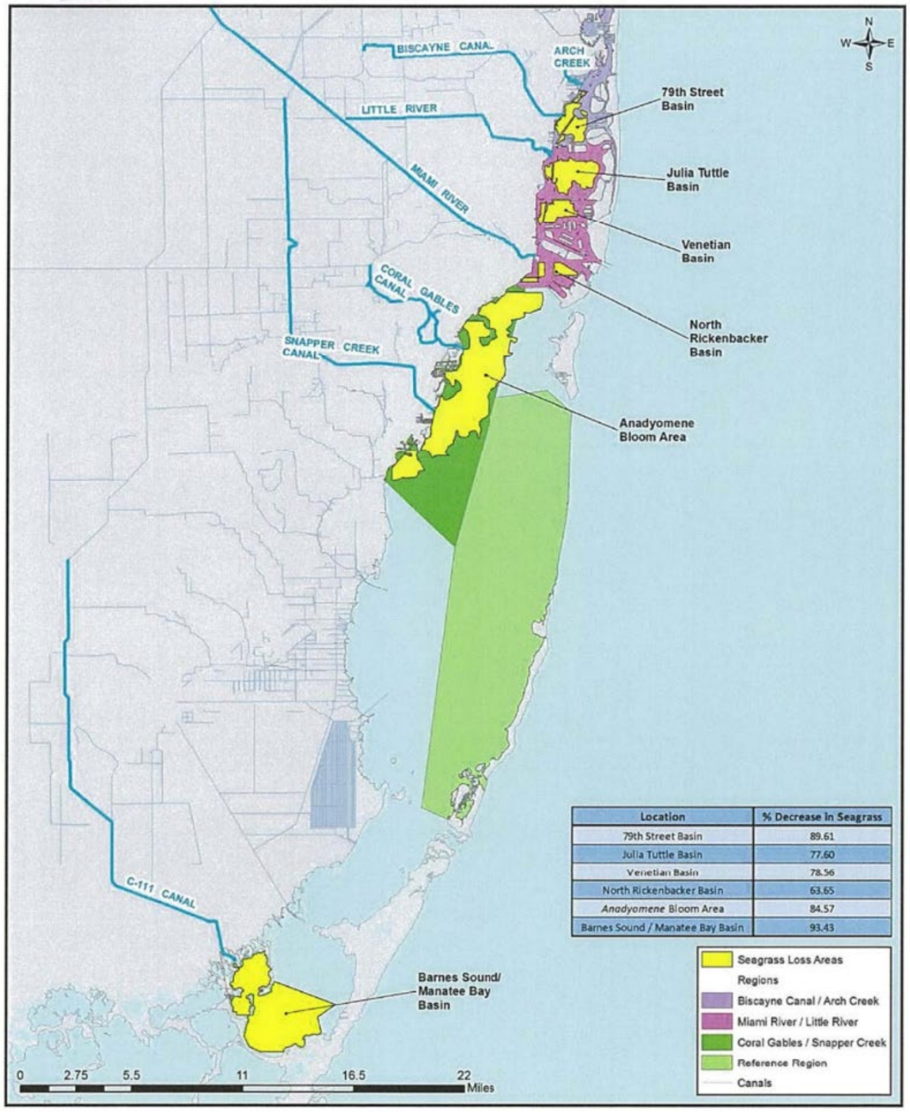


FIGURE 5-13 Trends in chlorophyll a concentration from 1995 to 2015 in (a) North, (b) Central, and (c) South Biscayne Bay. Note that the scale on the top graph is 2.5 times greater than the lower plots. Red horizontal lines represent chlorophyll a water quality criteria established for the Bay; the two lines in panels (a) and (c) indicate different chlorophyll a criteria for different portions of the North and South Bay. SOURCE: Millette et al., 2019.

Ecological implications. The ecological conditions of Biscayne Bay are increasingly affected by human activities that may limit the ability of the CERP to reach its goals. For example, seagrass communities in the north and central bay were relatively stable until 2005 when hypersalinity and increasing chlorophyll a concentration, associated with a series of algal blooms, led to extensive seagrass losses. Cumulative losses amount to 65 percent, or 21 mi^2 of seagrass over the past decade, including nearly half the manatee grass (Figure 5-14; Millette et al., 2019). Specific seagrass habitat losses between 2005 and 2018 include a 77 percent decrease in the Julia Tuttle basin, decreases of 90 percent in the 79th Street Basin, 66 to 89 percent north of Rickenbacker Causeway, and 93 percent in Barnes Sound and Manatee Bay basins (DERM, 2019; Figures 5-14 and 5-15). The die-off of seagrasses in Barnes Sound and Manatee Bay in the South Bay occurred in 2005 following Hurricane Katrina, which generated high volumes of nutrient-rich runoff and led to a multiyear algal bloom. These changes, combined with mangrove clearing during the expansion of US Highway 1 (Figure 5-12), have led to the loss of nearly all seagrasses in this area of the Bay (Rudnick et al., 2012). Few of these losses have shown any sign of recovery and chlorophyll a concentrations remain elevated (DERM, 2019).



Location	% Decrease in Seagrass
79th Street Basin	89.61
Julia Tuttle Basin	77.60
Venetian Basin	78.56
North Rickenbacker Basin	63.65
Anadyomene Bloom Area	84.57
Barnes Sound / Manatee Bay Basin	93.43

FIGURE 5-14 Map of change in seagrass extent in Biscayne Bay. Die-off is particularly severe in north Biscayne Bay. SOURCE: Gimenez, 2019.

FIGURE 5-15 Seagrass die-off in Biscayne Bay at sampling station BH 14 between June 2016 (far left) and June 2017 (far right). SOURCE: DERM, 2019.

Currently, the nearshore seagrass community (from Matheson Hammock to Turkey Point) is dominated by shoal grass (*Halodule wrightii*) and turtle grass (*Thalassia testudinum*), with very little cover of manatee grass (*Syringodium filiforme*) (RECOVER, 2019). Turtle grass, a marine seagrass species that is intolerant of brackish conditions, is now dominant in many areas where seagrasses are present (DOI, 2006). The co-occurrence of *Halodule* and *Thalassia* is described as a desired goal of CERP and was found, on average, at 58 percent of monitoring sites from 2008 to 2017. Estimates of cover (i.e., the area occupied by a species per unit area) for all these species is low, ranging from 17.1 percent for *Halodule*, 9.1 percent for *Thalassia*, and only 0.2 percent for *Syringodium* over the period of record (RECOVER, 2019), illustrating the tenuous hold that seagrasses have in Biscayne Bay.

For Biscayne Bay overall, Millette et al. (2019) predict a regime shift from a system with clear water and extensive seagrass meadows to a murky system dominated by phytoplankton with reduced benthic nursery habitat. The conditions leading to this tipping point are worsening; phosphorus and chlorophyll a levels are increasing and the system response is exacerbated by other stressors related to climate change such as salinity and increasing water temperatures (Miami-Dade Circuit Court, 2018; Millette et al., 2019). The possibility of seagrass recovery is limited; RECOVER (2019) considers the future of Biscayne Bay's seagrass meadows as "bleak."

Increasing salinity associated with sea-level rise and a lack of freshwater inflows affects not only seagrass but also animals who depend on mesohaline conditions, including the oyster (*Crassostria virginica*), American crocodile (*Crocodylus acutus*), spotted seatrout (*Cynoscion nebulosus*), silver perch (*Bairdiella chrysoura*), and mojarras (*Eucinostomus spp.*) (Bellmund et al., 2004). For these and other species, abundance decreases rapidly as salinity increases (Figure 5-16; Serafay et al., 1997). Estuarine fish species, such as red drum and black drum, have been replaced with euryhaline and marine species (McManus et al., 2014; Serafy et al., 2003). In the nearshore zone, the persistence of mesohaline conditions remains far from CERP targets, with the maximum duration of consistent mesohaline conditions ranging from 3 to 20 days in the wet season (target is 34 days) and 5 to 36 days for the dry season (target is 78 days) (RECOVER, 2019). Biscayne Bay National Park developed its own salinity targets for the western zone of the Park that are more restrictive than the CERP targets, with an overall standard that salinities should never exceed 30 PSU, and specific targets of 15-25 PSU for all of March through August, and less than 20 PSU in September through October (the late wet season). Biscayne Bay National Park also set a target for the coastal mangrove zone in the park of 0-5 PSU. Without more freshwater inflow to Biscayne Bay, the conditions will remain insufficient to support species adapted to mesohaline conditions.

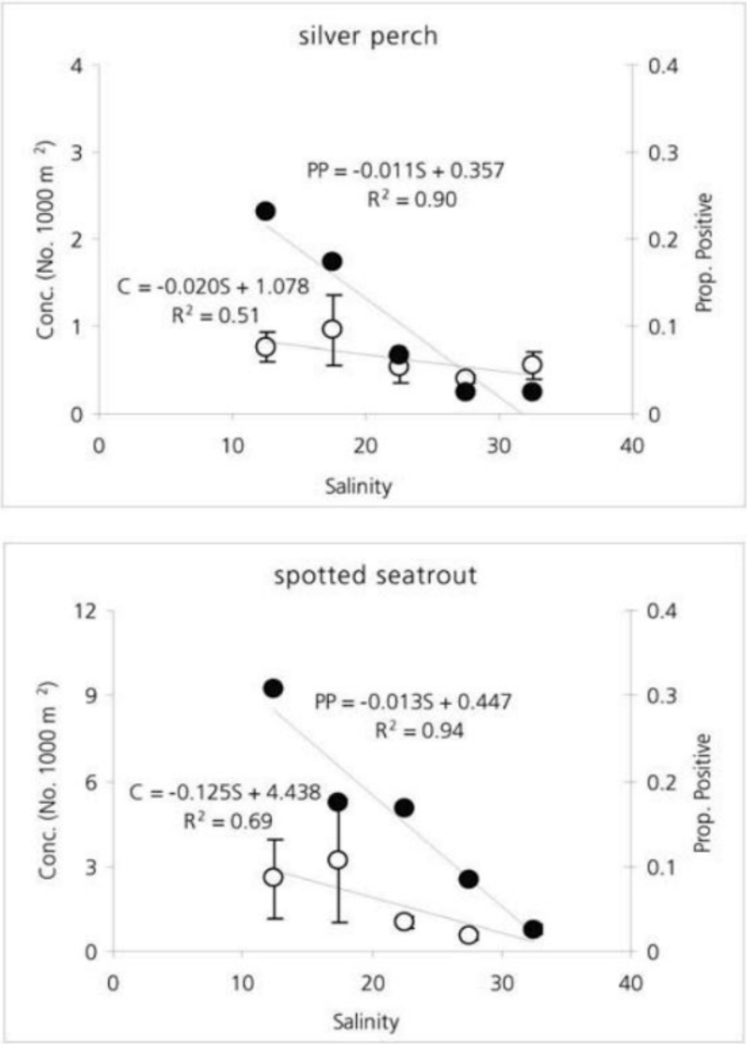


FIGURE 5-16 Abundance of key indicator fish relative to salinity (note open circles are concentration of juvenile fish (per 1,000 m^2), closed circles indicate species abundance (as the proportion of positive tows—sampling tows in which the fish species was caught). Note the "S" in the regression relationships refer to salinity. SOURCE: DOI, 2006.

Restoration Goals and Expected Effects of Planned CERP Projects

The 2007 Interim Goals Agreement (USACE et al., 2007) describe the early qualitative hydrologic and ecological expectations from the CERP for Biscayne Bay:

- Increase freshwater flows;
- Reduce the intensity, duration, frequency, and spatial extent of high-salinity events, reestablish low-salinity conditions in mainland nearshore areas, and reduce the frequency of and rapidity of salinity fluctuations resulting from pulse releases of freshwater from canals; and
- Increase densities of juvenile shrimp.

In addition, RECOVER monitors a set of indicators including seagrass (species occurrence, cover, density), chlorophyll a concentration (as a measure of phytoplankton blooms), characteristics of the mangrove fish community (species frequency of occurrence, density), epifauna adapted to mesohaline conditions including juvenile pink shrimp density (e.g., Browder and Robblee, 2009), and crocodile growth rates (RECOVER, 2019).

Yellow Book projections for Biscayne Bay. To achieve these goals, the CERP was envisioned in the Yellow Book to improve the distribution of existing flows and provide additional water supply (77,000 acre-feet/year—a 6 percent increase in total freshwater inflows [including canal discharges] compared to existing conditions[13]). These hydrologic improvements were expected to "create conditions that will be conducive to the reestablishment of oysters and other components of the oyster reef community" and "reestablish productive nursery habitat all along the shoreline" in Biscayne Bay (USACE and SFWMD, 1999). The CERP was also expected to rehydrate coastal wetlands and reduce point-source freshwater discharges to Biscayne Bay.

The lack of baseline information on predrainage conditions has limited the development of CERP freshwater flow targets for Biscayne Bay (McManus et al., 2014; RECOVER, 2011a). The Yellow Book acknowledged that a detailed analysis was needed to define specific hydrologic targets considering the feasibility of potential water sources, although this feasibility study was never completed. DOI (2008) estimates that at least 440,000 acre-feet/year in additional freshwater flows are needed to meet salinity (<30 ppt) and ecological targets in the nearshore area associated with the National Park (between the S-22 and S-197 structures). DOI (2008) states that the bulk of flows are needed during the late dry season to early wet season—a time when water availability is typically extremely limited. To date, freshwater flow targets for Biscayne Bay from the CERP and a plan to meet those targets have not been established.

Expected effects of planned CERP projects. Two current CERP projects offer benefits for Biscayne Bay: the Biscayne Bay Coastal Wetlands (BBCW) Phase 1 Project, now under construction (see Chapter 3), and the Biscayne Bay and Southeastern Everglades Ecosystem Restoration (BBSEER) Project, which launched its 3-year planning process in 2020 (USACE and SFWMD, 2020b). The BBCW project was divided into two phases to make incremental progress without near-term sources of new water. Phase 1 (see Chapter 3) diverts existing canal flows through the coastal wetlands to improve the salinity distribution in the coastal wetlands. The project is expected to rehydrate about 400 acres of freshwater wetlands and improve mesohaline conditions in at least 6,300 acres of saltwater wetland. The project would also reduce salinities in at least 2,900 acres of nearshore habitat by diverting an average of 59 percent of the annual coastal structure discharge into coastal wetlands (USACE and SFWMD, 2012). The planned diversions of canal water through the existing coastal wetlands are also anticipated to provide water quality benefits such as a reduction of 50 percent of the projected future nitrate load to Biscayne Bay (162 metric tons per year), although water quality improvement was not an explicit design objective of the project (USACE and SFWMD, 2012). Although there have been some improvements in salinity from BBCW Phase 1 to date, benefits have been limited by a lack of available freshwater (see Chapter 3). Overall, Phase 1 benefits are focused toward improved conditions in the coastal wetlands using existing flows, with relatively modest benefits to nearshore habitats, given the lack of additional water supply.

The BBSEER project is envisioned as a regional planning effort that encompasses a number of projects from the Yellow Book, including additional elements from the BBCW project not covered in Phase 1 (including in the Model Lands in South Biscayne Bay) and the eastern components of the C-111 Spreader Canal project. It may also consider wastewater reuse in Miami-Dade County and Lake Belt storage features proposed in the Yellow Book (USACE and SFWMD, 1999). The specific benefits of BBSEER, which will be determined in the project planning process, will likely depend on the availability of new freshwater inflows.

Implications of Environmental Issues for CERP and Non-CERP Efforts

During the ongoing implementation of BBCW Phase 1, eutrophication of this historically oligotrophic system has increased, particularly in the North Bay (Millette et al., 2019; Figure 5-13). As

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[13] Relative to 2004 water budget (SFWMM v5.4); see NRC, 2005.

with the northern estuaries, the CERP did not consider the potential impacts of nutrient enrichment and algal blooms when setting restoration goals for Biscayne Bay. Without substantial new non-CERP efforts to address water quality, the complications of eutrophication may affect progress toward CERP ecological goals, not only for chlorophyll a targets but also in reestablishing nearshore nursery habitat for fish and other fauna (RECOVER, 2019). Increasing nutrient concentrations and algal blooms are hypothesized to have pushed the system toward a tipping point for a full-scale regime shift to an ecosystem dominated by algae and the loss of seagrass beds in the open waters of the Bay (Millette et al., 2019). Crossing such a threshold would be catastrophic for Biscayne Bay and could make the CERP's ecological objectives difficult to achieve.

Key Questions for Decision Makers on Restoration of Biscayne Bay

As with the other South Florida estuaries, there are key management questions that must be answered to make sound decisions on Biscayne Bay restoration. For example, what is the timing, magnitude, and spatial distribution of freshwater inflows needed to meet restoration goals? Both federal and state programs are at work on water quality issues in Biscayne Bay, but they often work independently in the pursuit of common goals. It is vital to address the issue of water quality (a state responsibility) as a driver of Biscayne Bay conditions to meet the CERP targets for chlorophyll a and seagrass. Decisions will be needed to respond to changes in external drivers associated with climate change that will foster the long-term resilience of the system, and this will take cooperation across many groups working in Biscayne Bay. Because management decisions inevitably involve trade-offs, managers will need a sound set of integrated science tools to inform questions such as those posed in Box 5-6.

BOX 5-6 Key Questions Relevant to Biscayne Bay Management Decisions

1. What are the appropriate, spatially explicit goals for freshwater inflows required to meet CERP goals in the nearshore zone of Biscayne Bay?

- What is the appropriate quantitative target for freshwater flows to Biscayne Bay and how will increased flows affect ecological conditions? How do these inflows affect saltwater intrusion?
- How can new sources of freshwater be made available and delivered to Biscayne Bay?
- How does the timing of restoration actions affect what is achievable?
- What are the larger-scale trade-offs between increasing flow to Biscayne Bay and restoration of Everglades National Park/Taylor Slough/Florida Bay (i.e., are they in competition for water at some scale)?

2. Is meeting the CERP goals for Biscayne Bay at risk if increasing nutrient concentrations, which are largely outside of the purview of the CERP, are not addressed?

- If the bay is nearing an ecological tipping point in which it will change from a clear-water, seagrass-dominated system to a turbid, algal-dominated one, can the CERP mitigate this transition? If so how and for how long?
- What are the effects of increased CERP flows on Biscayne Bay water quality?

3. How can water management foster greater ecological resilience in light of climate change and sea-level rise?

- How will sea-level rise and increasing temperatures impact the Biscayne Bay ecosystem (water and nutrient budgets, light penetration, coastal erosion, ecological function) and what is achievable from CERP in Biscayne Bay?

Science Support for Restoration Management Decisions in Biscayne Bay

Science-based tools for decision making are part of a valuable toolkit to ensure decisions are informed by an understanding of the trajectories of ecosystem response to management actions and environmental change. Climate change impacts are increasing, and nutrient inputs from an increasing human population are fundamentally restructuring the Bay's drivers and ecological responses. A combined set of conceptual models, monitoring data, synthesis, and models (see Figure 5-17 and Table 5-7) can characterize and quantify the relative effect of the quantity and timing of freshwater delivery and water quality on CERP restoration targets, while separating those effects from other external and internal drivers and feedback mechanisms that also contribute to biological responses. Without this understanding, the accumulation of monitoring data leaves efforts to restore Biscayne Bay "data rich and information poor." In this section, the committee reviews the status of this science relative to key management questions aimed at informing CERP science priorities.

Hydrologic science and modeling tools. Although increased freshwater flows to improve nearshore salinity in Central and South Biscayne Bay are a primary goal for the CERP, no quantitative, seasonally variable goals for freshwater flow delivery to meet restoration targets have been established (RECOVER, 2011a). One challenge for restoration of Biscayne Bay is that hydrologic and biological data on the predrainage system are almost entirely lacking, making identification of restoration flow targets challenging (McManus et al., 2014). Without this understanding, modeling tools are essential to evaluate the conditions and flows necessary to generate the desired ecological responses and to predict expected outcomes from project alternatives. This is also needed to understand the effects of shifting baseline conditions expected under a changing climate. Climate change and sea-level rise now present new challenges for the feasibility of meeting restoration salinity targets (Graham et al., 2020), and these impacts need to be understood in order to inform restoration investments that will provide long-term benefits.

Freshwater flows to Biscayne Bay include groundwater discharge from the Biscayne aquifer, which extends westward into Everglades National Park, and surface water inflows from canals supplied with water released from the Everglades ecosystem as well as inputs from local watersheds. Attainment of nearshore restoration goals will require modeling of the interactions of saltwater and freshwater from both surface- and groundwater flows to evaluate the potential effects of the CERP across a range of conditions. The Regional Simulation Model for the Everglades and Glades Lower East Coast Service Area (RSM-GL) can be used to simulate overland flows and water management to the coastal region of Biscayne Bay, but it is entirely a land-based model not suited for predictions of coastal zone conditions. The recent Biscayne and Southern Everglades Coastal Transport (BISECT) model (Swain et al., 2019) simulates surface water and three-dimensional groundwater flow and exchanges between these flow regimes. The model, based on the code of the Flow and Transport in a Linked Overland/Aquifer Density Dependent System (FTLOADDS) (Wang et al., 2007), also simulates groundwater and surface-water salinity and temperature, based on hydrologic data from 1996-2004. BISECT supports evaluation of the effects of water management changes combined with sea-level rise scenarios on South Florida hydrology. The model domain includes coastal zones, but the primary focus is to answer questions about hydrologic conditions on land and in tidal wetlands, rather than conditions within the Bay itself. Calibration of the model used extensive hydrologic data available from Everglades National Park, including Florida Bay, but did not employ flow data from surface discharges to Biscayne Bay. As such, the performance is much better for Florida Bay than Biscayne Bay. However, this model has the potential to fill an important gap in the southern Everglades coastal region, bridging between the land-based hydrologic models (e.g., RSM-GL) and estuarine hydrodynamic models in the coastal region where the RSM performs poorly (Mills et al., 2019). It also provides a tool for more effectively capturing the effects of sea-level rise on coastal areas. BISECT model development relied on long-term monitoring data that refined the understanding of the relationships between factors such as (a) the rates of water flow in canals, marshes, and aquifers; (b) the nature of freshwater and saltwater mixing in surface waters; and (c) the rates of freshwater and saltwater exchange between surface water and groundwater in both onshore and offshore

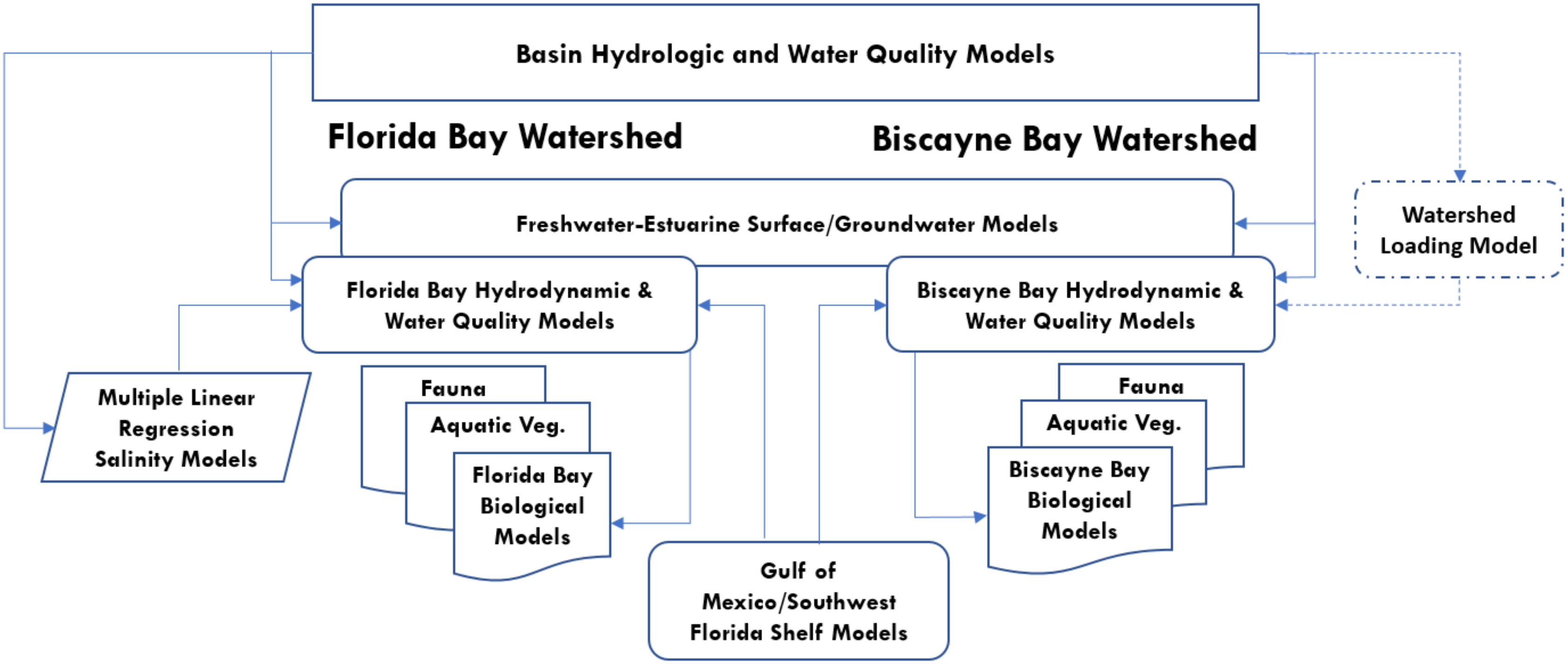

FIGURE 5-17 Conceptual illustration of the modeling capabilities that can be used to investigate restoration outcomes in southern estuaries. Note that boxes in dashed lines (e.g., Biscayne Bay watershed loading models) represent capabilities that have not yet been developed.

TABLE 5-7 Examples of Hydrologic, Hydrodynamic, Water Quality, and Ecological Models Applicable to Florida Bay and Biscayne Bay

Name and Lead Agency	Domain	Description
Hydrologic Models		
Regional Simulation Model (RSM) and Natural System RSM (NRSM)	Everglades and Lower East Coast	The RSM simulates surface and groundwater hydrology for current or future (RSM) or predrainage (NSRSM) conditions in response to historic climate records and data. The model outputs water levels and flows from canals, water control structures, local topography and storage reservoirs, etc. It simulates the movement and distribution of water in conjunction with the coordinated operation of canals and structures (Bras et al., 2019; SFWMD, 2005)
Hydrologic Engineering Center River Analysis System (HEC-RAS)	Everglades	A hydrodynamic model that simulates the channel flow regimes of canals, rivers, and channels
Biscayne and Southern Everglades Coastal Transport (BISECT)	Florida Bay, Biscayne Bay	Evaluates drivers of South Florida surface and groundwater water and salt budgets to evaluate seepage barrier efficacy and alternative water-management practices and sea-level rise by combining the Tides and Inflows to the Mangrove Everglades (TIME) and FTLOADDS simulator (Swain et al., 2019)
Hydrodynamic and Water Quality		
Flux Account for Tidal Hydrology at the Ocean Margin (FATHOM/BAM)	Florida Bay	Spatially explicit 54-basin box model that simulates the Florida Bay water and solutes in response to runoff, climate, tides, and the topography of the Bay by tracking mass-balance of water, salt, nitrogen and phosphorus (N&P), dissolved oxygen (DO), and heat
Curvilinear Hydrodynamics in 3-D (CH3D)	Biscayne Bay	3D estuarine hydrodynamic model with time-varying salinity and temperature
Multi-Dimensional Sediment (TABS-MDS)	Biscayne Bay	2D finite element hydrodynamic and salinity model intended to support CERP freshwater flow scenarios
Biscayne Bay Simulation Model (BBSM)	Biscayne Bay	3D density-dependent flow model designed to evaluate the effects of surface- and groundwater flows and redistribution on salinity
Environmental Fluid Dynamics Code (EFDC)	Florida Bay	A 3D estuarine hydrodynamic model that transports salinity, heat, sediments, and toxic contaminants (e.g., metals or organics). The EFDC integrated water quality model HEM-3D was not completed for Florida Bay
South Florida Hybrid Coordinate Model (HYCOM)	Florida Bay	A coastal hydrodynamic model of South Florida coastal seas developed to provide boundary conditions for the EFDC Florida Bay model
Multiple linear regressions	Florida Bay	Multiple statistical models relating southern Everglades hydrologic (e.g. water level), marine, and weather data to predicted salinity at 37 estuarine index areas of ENP (Marshall et al., 2011)
Biscayne Bay Box Model	Biscayne Bay	Water quality box model that estimates the long-term average N&P concentrations and loads in the Bay based on total phosphorus and dissolved in organic nitrogen loads from canals, ungauged surface water, groundwater, atmospheric, and Atlantic Ocean contributions.
Ecological Models		
Seagrass Ecosystem Assessment and Community Organization Model (SEACOM)	Florida Bay	SEACOM is a mechanistic, physiological unit model that predicts seagrass community type response to salinity and water quality, climate and climate change on seagrass distribution, species composition and habitat suitability for higher trophic levels; used to evaluate restoration alternatives (Madden et al., 2016)

(Continued)

TABLE 5-7 Continued

Name and Lead Agency	Domain	Description
Ecological Models		
Seagrass Habitat Suitability Index	Biscayne Bay	Statistical seagrass habitat suitability models of that predict *T. testudinum* and *H. wrightii* as a function of light, depth, salinity. and temperature (Santos and Lirman, 2013)
Seagrass Discriminant Function model	Florida Bay	Florida Bay statistical models that predict occurrence of eight seagrass community types based on FATHOM-predicted water quality, including total organic carbon, nitrate, ammonium, total phosphorus, and salinity (Herbert et al., 2011)
Crocodile Habitat Suitability Index	Florida Bay	Predicts habitat based on crocodile growth and survival, which is a function of salinity and prey biomass (Mazotti et al., 2009)
Shrimp statistical models	Biscayne Bay	Predict pink and grass shrimp as a function of salinity, water temperature, depth, and seagrass (Zink et al., 2017)

areas. However, the accuracy of the model remains limited by the lack of monitoring data in some areas, prompting calls, for example, for increased monitoring of groundwater levels (Mills et al., 2019). Overall, models that link inland watersheds with the hydrodynamics of estuarine and coastal waters remain insufficient to address fine-scale spatially explicit water distribution issues, groundwater–surface water exchange, saltwater intrusion, and the resulting effects on biota. Improving model performance will depend on the integration of additional data (e.g., geomorphology, water levels) to capture these biophysical feedbacks. To date, BISECT has not been approved for use in CERP planning.

Models that quantitatively link surface- and groundwater inflows to nearshore salinity in Biscayne Bay are essential to CERP planning and near-term decision making. Salinity monitoring in the Bay has been foundational to estuarine hydrodynamic studies that have solidified an understanding of Biscayne Bay's hydrodynamic circulation and links to freshwater flow. Modeling studies have quantified surface-water and groundwater inputs into Biscayne Bay (e.g., Langevin et al., 2001) and 2D and 3D hydrodynamic circulation models exist (Brown et al., 2003; Wang et al., 2003). The Biscayne Bay Simulation Model (BBSM) is a three-dimensional density-dependent flow model designed to evaluate the effects of surface- and groundwater flows and redistribution on salinity. This model was recently revised to improve its ability to predict salinity along the shoreline, in part by adding a groundwater component that had been omitted from the previous model version because of uncertainties about groundwater flows. In this most recent model update (BBSMv4), the predicted salinity values more closely matched the observed distributions of nearshore salinities and the model was able to reproduce observed seasonal salinity patterns, with lower salinity during the wet season and higher salinity in the dry season. However, the improvements in model performance were attributed to a substantial increase in simulated groundwater flow volumes, which were required to more accurately predict nearshore salinity during portions of the year, suggesting that the existing estimates of groundwater flow to Biscayne Bay (e.g., Stalker et al., 2009) may be underestimated (Stabenau et al., 2015). Model improvements have increased the understanding of nearshore salinity patterns, but the relationship between various freshwater inflows and salinity are not fully understood.

Understanding the linkages between water quality and ecological response. Many of the current ecological issues facing Biscayne Bay, particularly in the North and Central Bay, are a result of increasing nutrient concentrations (phosphorus and nitrogen), and elevated chlorophyll a concentrations that have led to seagrass die-offs. Currently, these issues are most severe in the open waters of the Bay (i.e., beyond the nearshore zone) that is not the focus of the CERP. However, the Bay's deteriorating conditions have an impact on the nearshore zone and may limit the ability of the CERP to meet the restoration targets that have been established. To understand the potential implications of changes in water quality to CERP goals for Biscayne Bay, efforts are needed that connect monitoring data, synthesis, and hypotheses with linked hydrodynamic and water quality models that, in turn, will inform ecological response models that predict recovery trajectories relative to CERP performance targets (e.g., seagrass diversity, cover, and density; chlorophyll a concentration).

A strong monitoring effort is ongoing in Biscayne Bay to support this objective. The Integrated Biscayne Bay Ecosystem Monitoring and Assessment Program[14] is a strategic multiagency monitoring effort that produces quantitative data on some of the key RECOVER systemwide indicators that have quantitative performance targets (Lirman et al., 2014; RECOVER, 2019). Together with monitoring from partner agencies, these monitoring data are instrumental in documenting salinity, nutrient concentrations, and eutrophication in the Bay and the loss of large areas of seagrass.

In addition to the limitations of hydrodynamic models to predict spatially explicit salinities (discussed in the previous section), the lack of water quality models, both in the watershed and in the estuary, is a key gap in advancing restoration in Biscayne Bay. A nutrient box model (Marshall and Nuttle, 2011) was developed to estimate nutrient loads from watershed sources using mass-balance calculations, with estimates of long-term average nutrient concentrations for total phosphorous,

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[14] See https://marine-biology-ecology.rsmas.miami.edu/research-themes/centers-and-labs/benthic-ecology-coral-restoration-lab/ibbeam/index.html.

BOX 5-7 Evolution of Louisiana's Landscape Model

In the early 2000s, Louisiana coastal scientists and engineers (from academia, the private sector, and government agencies) largely worked in groups based on background and discipline. Each modeling group performed their own analysis (hydrodynamics, water quality, ecology, etc.). One-way information transfer, when it occurred, was from one group to another.

Analysis for the 2012 Louisiana Coastal Master Plan was the first major attempt at coupling the modeling components where the information passage (as shown in Figure 5-18) included feedback among the various components. For example, the ecohydrology output was used to drive the wetland morphology and vegetation modules, while feedback from the vegetation and wetland morphology modules also influenced ecohydrology. This early attempt at coupling the various landscape modeling components occurred once every 25-years (within a 50-year simulation), and the information passage was largely manual.

In the 2017 cycle of the Louisiana Coastal Master Plan, the various modules (ecohydrology, wetland morphology, vegetation, etc.) were merged into a master code (Figure 5-18) that allowed for a stronger integration. Furthermore, the full feedback among the various subroutines occurred on an annual basis. The feedback among the components is essential for comprehensive "trade-off" analysis where, for example, projects that provide benefit for one habitat metric decrease another. It was also used to evaluate alternatives and assess climate change impacts. Additionally, the temporal and spatial feedback allows for capturing potential positive or negative synergy among proposed restoration and protection projects. This example highlights the importance of integrating various existing modeling tools, for example, the RSM with detailed groundwater modeling tools as well as coastal/estuary tools.

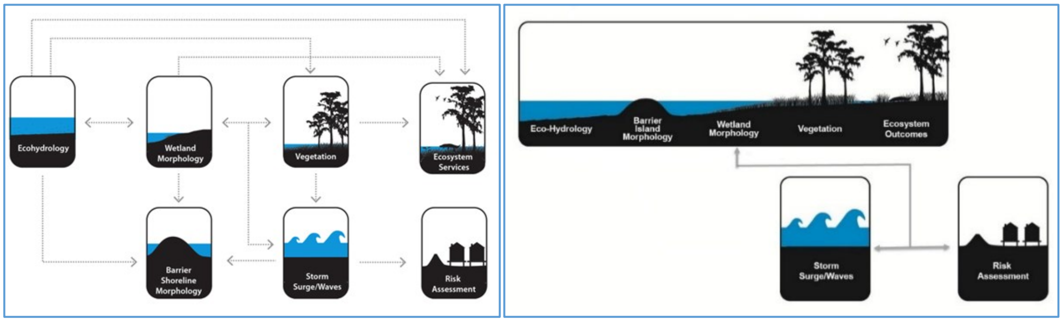


FIGURE 5-18 Left: Model structure used in the 2012 Louisiana Coastal Master Plan. Right: Model structure used in the 2017 Louisiana Coastal Master Plan. SOURCE: https://coastal.la.gov/our-plan.

ammonium, nitrate-nitrite, and dissolved inorganic nitrogen. However, the model has limited success in describing the variability in nutrient concentrations, with predicted values of total phosphorus 17 to 44 percent higher than measured values, and predicted nitrate-nitrite values 1.5 and 4 times higher than measured values (Marshall and Nuttle, 2011). The latter was attributed to losses due to denitrification that were not accounted for in the model. The box model was used to inform development of the Biscayne Bay nutrient criteria (Briceno et al., 2011); recently Biscayne Bay was put on the 303(d) list for impaired water quality due to elevated chlorophyll a (FDEP, 2017). The TMDL is in the planning stages, but will provide the impetus needed to develop a more comprehensive synthesis and development of water quality modeling capabilities. This water quality model could be used as input to predict possible CERP outcomes for seagrass and other biota under scenarios of freshwater flow and various water quality trajectories.

The development of ecological response models for Biscayne Bay has lagged, particularly in comparison to efforts for Florida Bay. The large seagrass die-offs in the north and central portions of the Bay demonstrate the need for models that facilitate a deeper understanding of the drivers of nutrient loading into the Bay, corresponding ecological responses, and potential interactions with sea-level rise. A Biscayne Bay conceptual ecological model (Browder et al., 2005) describes the salinity regime and links between stressors and key ecosystem attributes, but subsequent development of quantitative ecological models has been limited. Currently, there is a seagrass HSI model (Santos and Lirman, 2012), with presence/absence predictions based on light, depth, salinity, and temperature. However, the relative contributions of light limitation from water color, turbidity, and chlorophyll a are not specifically distinguished in this seagrass HSI, limiting the model's utility to integrate CERP restoration discussions with water quality management. More recently, statistical models have been developed (McManus et al., 2014; Santos et al., 2020), including work linking algal blooms to seagrass extent that demonstrated the ability of algal blooms to fragment seagrass patches, significantly altering seagrass community structure (Santos et al., 2020). Continuing work is needed to develop the toolkit for the ecological response of Biscayne Bay that will inform management decisions, such as the optimal flows needed for the recovery and persistence of seagrasses. As with the northern estuaries, it is likely that more mechanistic, physiologically based models that can predict ecological outcomes under conditions that have not yet been experienced (e.g., sea-level rise, warming) will be needed to address questions about system response to the novel set of environmental conditions that climate change will bring.

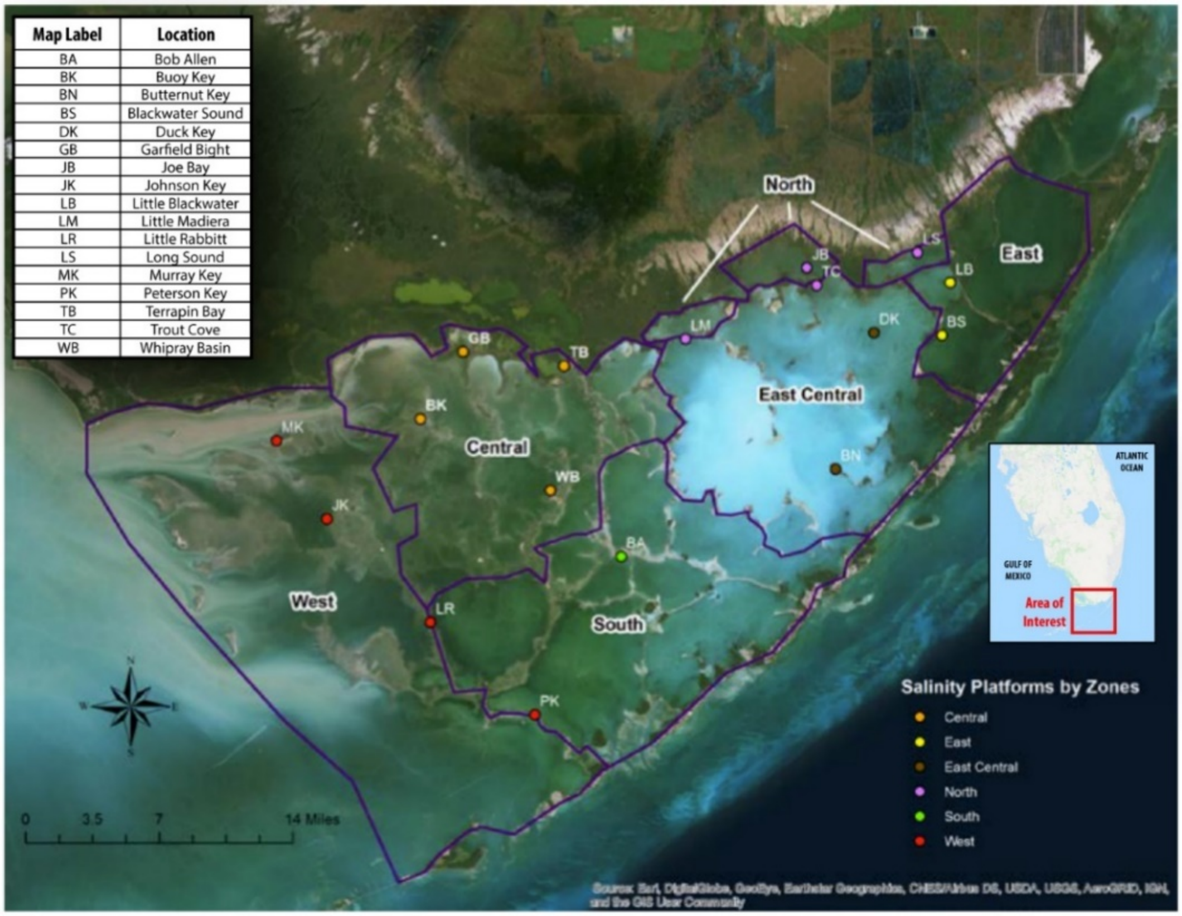
In the long term, an integrated modeling approach, coupling hydrology, water quality, hydrodynamic, and seagrass or other ecological models, is needed to link CERP freshwater inflows to the RECOVER performance indicators and to identify thresholds and tipping points in the system that may lead to irreversible changes (for an example, see Box 5-7). Future investments in this initiative would provide an important management tool for decision makers trying to identify CERP and non-CERP management strategies necessary to understand the trade-offs and relative costs and benefits among CERP projects affecting the southern coastal systems to meet restoration goals. For example, both Biscayne Bay and Florida Bay need additional freshwater flows but plans to send water south will have differential benefits for each ecosystem. Modeling tools that weigh differential benefits can provide information that will make clear the consequences of possible management decisions.

Florida Bay

Florida Bay is a large, shallow marine lagoon, bounded to the north by the Florida peninsula and to the south and east by the Florida Keys. The western side is a relatively open connection to the southwest Florida shelf, and exchanges occur mainly through physical forcing via winds and tides (Wang et al., 1994). Most of its approximately 2,200 km^2 is located within the boundaries of Everglades National Park, and its unique geomorphological structure supports a mosaic of habitats, including freshwater marshes, mangroves, and abundant seagrass beds. Living organisms produce calcium carbonate (marl) sediments that form the base of the shallow bay along with extensive mud banks, which are generally exposed at high tide and divide the bay into a series of basins (Figure 5-19). Each basin has its own physical characteristics, providing a range of unique habitats that support many plants, invertebrates, fishes, birds, mammals, and reptiles, including several threatened and endangered species (e.g., the Florida manatee) and species of special concern (e.g., the roseate spoonbill). Circulation is complex; mud banks on the western side and the Florida Keys to the southeast significantly dampen tidal influences in the interior of the bay from the Gulf of Mexico and the Atlantic Ocean. This restricted circulation also makes Florida Bay prone to extremes of salinity, temperature, and reconfiguration of sediments by storms and other factors.

Environmental Changes and Their Ecological Effects

Hydrologic changes. As discussed in Chapter 2, drainage and flood control in the Everglades ecosystem for agricultural and urban development has vastly reduced freshwater flows to Florida Bay. Using paleoecologic data to improve existing models of predrainage conditions, Marshall et al. (2020) estimated that predrainage flows in Taylor Slough were approximately three times the recent observed flows (between 1990 and 2000) and predrainage Shark River Slough flows were approximately twice the recent observed flows. Today, the largest single source of freshwater into Florida Bay is direct rainfall over the Bay itself; for the period from 1970 to 1995, rainfall represented more than 90 percent of all



Map Label	Location
BA	Bob Allen
BK	Buoy Key
BN	Butternut Key
BS	Blackwater Sound
DK	Duck Key
GB	Garfield Bight
JB	Joe Bay
JK	Johnson Key
LB	Little Blackwater
LM	Little Madiera
LR	Little Rabbitt
LS	Long Sound
MK	Murray Key
PK	Peterson Key
TB	Terrapin Bay
TC	Trout Cove
WB	Whipray Basin

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

FIGURE 5-19 Map showing the locations of the Everglades National Park Marine Monitoring Network stations (squares) and six zones of similarity (Briceño and Boyer, 2010) in Florida Bay based on water quality characteristics (outlined in purple). SOURCE: Modified from RECOVER, 2019.

freshwater inputs to the Bay (Nuttle et al., 2000). In addition, the spatial distribution of freshwater inflows across the coastline have also changed. Current freshwater flows into the Bay are primarily from Taylor Slough (see Figure 4-2); flows from Shark River Slough that travel via currents into central and east central Florida Bay are minimal, typically occur only in the wet season, and have limited spatial influence (SFWMD, 2016b). Some additional flow can occur via another route; when water levels in Shark River Slough are high enough, the wet prairie area of the Rocky Glades (an area of karst that separates Shark River Slough from Taylor Slough and is seasonally flooded) may become inundated, and water flows south into Taylor Slough (Marshall et al., 2020). Under predrainage conditions, this flow would have contributed freshwater to North and Central Florida Bay (Figure 5-19).

With reduced freshwater inflows, and episodic high flows, the shallow coastal basins can experience significant excursions in salinity. Salinity in Florida Bay's coastal basins ranges from near zero in times of heavy rainfall and large freshwater inflows to above 60 ppt during conditions of drought and high evaporation (Stabenau and Kotun, 2012). Under highly localized precipitation events, both hypersaline and hyposaline conditions can exist simultaneously in different basins across the Bay. In 2015, Florida Bay experienced a 16-month, localized rainfall deficit, during which the Taylor Slough watershed received 25-35 inches of direct rainfall—the lowest total for any part of the SFWMD's 16-county region (SFWMD, 2016b). As a result of the rainfall deficit, salinity in the central coastal basins soared to over 70 ppt, the highest recorded salinities in 68 years of record (Park et al., 2016). Historically, freshwater flow from the Everglades, including Shark River flows that diluted Florida Shelf salinities in the Gulf of Mexico, maintained brackish conditions (< 30 ppt) over the entire bay and mitigated the development of hypersalinity in the northern Bay (Marshall et al., 2014) (Table 5-8). Under predrainage conditions, average salinities in North Florida Bay and northern portions of Central Florida Bay were less than one-third the salinity of seawater.

Water quality. Plant communities in most of Florida Bay are phosphorus limited because of very high nitrogen-to-phosphorus ratios in freshwater runoff, a long residence time for water, high rates of primary production, and carbonate sediments that sequester phosphorus (Figure 5-20; Fourqurean and Zieman, 2002; Fourqurean et al., 1992, 1993). The largest source of phosphorous to Florida Bay comes from the Gulf of Mexico, which stimulates seagrass growth in western, central, and southern portions of Florida Bay. Rudnick et al. (1999) estimated the phosphorus and nitrogen inputs into Florida Bay, and determined that watershed sources were minor for the Bay as a whole; the freshwater Everglades (Taylor Slough and the C-111 watershed plus Shark River Slough) contribute approximately 3 percent of all phosphorus inputs and 12 percent of all nitrogen inputs to the bay. Trends in phosphorus concentrations in Florida Bay over time appear relatively steady, with the exception of large hurricane events, which can elevate total phosphorus concentrations for up to 2 years afterward (Cole et al., 2018). Significant excursions of phosphate concentrations have also been observed after seagrass die-off events; Fredley et al. (2019) observed phosphate concentrations several times greater than pre-die-off levels in affected basins.

Following the 1987-1994 event, more than a decade of research ultimately uncovered a suite of interconnected contributing factors: hypersalinity caused by low freshwater inflows combined with high

TABLE 5-8 Comparison of Observed and Modeled Paleo-Based Salinities in Florida Bay

Region and zone in Florida Bay[a]	Map ID[a]	Station	Observed mean salinity	Mean paleo-salinity	Salinity difference (Obs – Paleo)
Northern margin (zones 1 & 5)	TB	Terrapin Bay	23.6	3.5	20.1
	GB	Garfield Bight	28.9	10.3	18.6
	LM	Little Madeira	23.8	8.2	15.6
	TC	Joe Bay	15.4	2.7	12.6
Eastern (zone 2)	BN	Butternut Key	31.3	17.7	13.6
	DK	Duck Key	29.0	16.8	12.2
Central & Western (zones 3, 4, 6)	BA	Bob Allen	33.2	21.1	12.1
	BK	Buoy Key	32.8	22.2	10.6
	JK	Johnson Key	35.3	27.0	8.3
	MK	Murray Key	33.0	24.8	8.2
	LR	Little Rabbit	34.4	27.3	7.1
	PK	Peterson Key	35.8	30.5	5.3

NOTES: See Figure 5-19 for locations. Based on output from the linkage between linear regression models and paleoecological data. Time periods for observed data range from 1998 to 2002 (see Marshall et al., 2009). The simulated paleo-based salinities are based on estimates for circa 1900 AD segments of the cores used to adjust existing hydrologic models that incorporate the 1965-2000 climate data.
SOURCE: Wingard, 2017. Reprinted with permission; copyright 2017, Springer Nature.

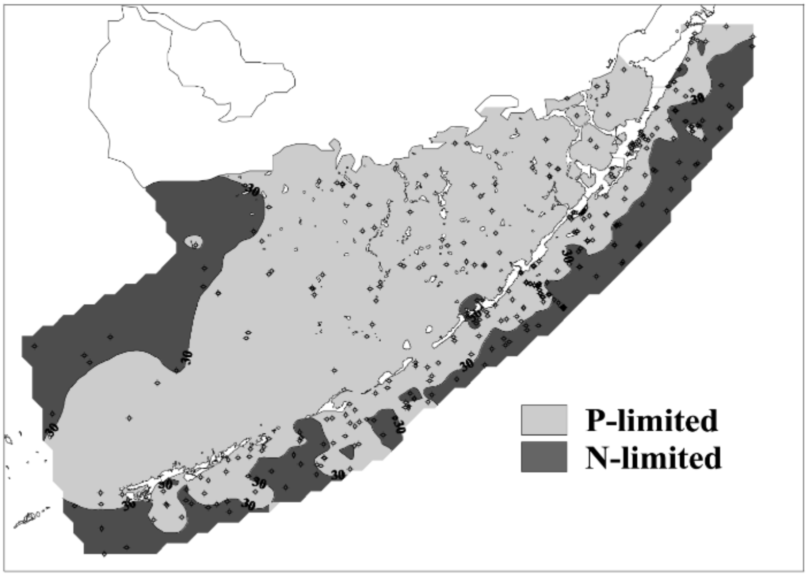


FIGURE 5-20 Zones of nitrogen (N)- and phosphorus (P)-limited seagrass communities in Florida Bay. The nitrogen-limited condition is N:P < 30; the phosphorus-limited condition is N:P > 30. SOURCE: Fourqurean and Zieman, 2002. Reprinted with permission; copyright 2002, Springer Nature.

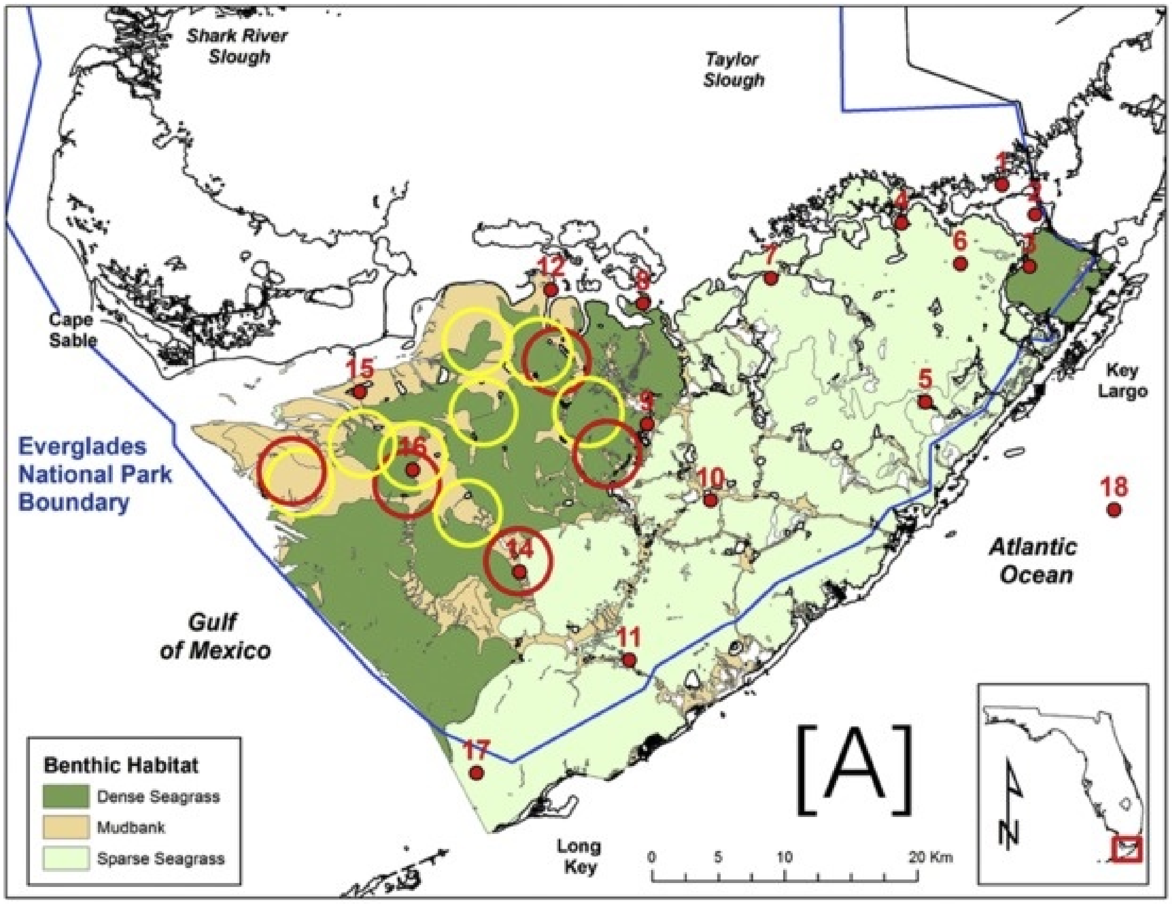
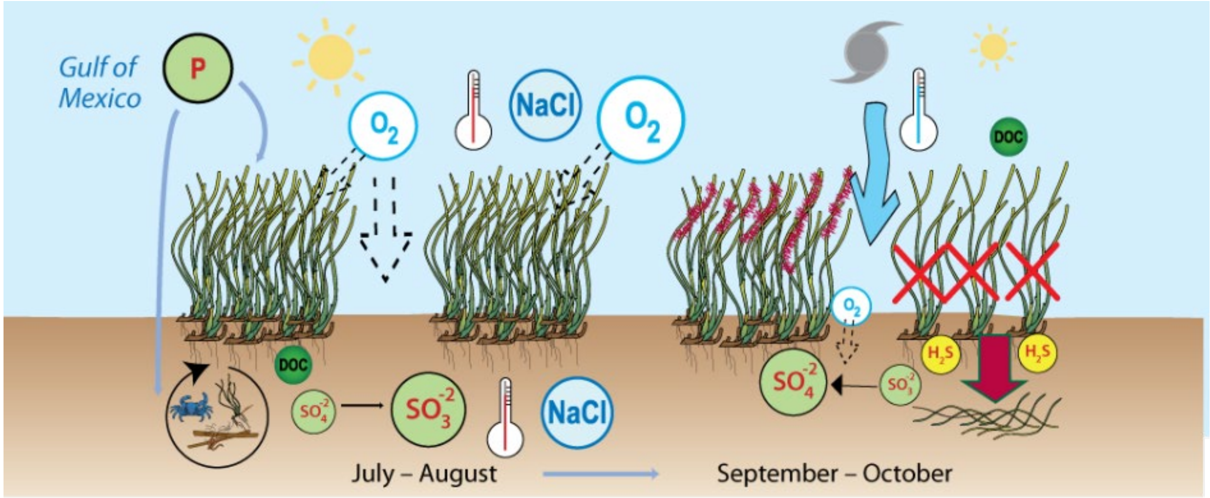


FIGURE 5-21 Comparison of locations of seagrass die-off in 1987 (red circles) and 2015 (yellow circles). SOURCE: Carlson et al., 2018.

temperatures in areas with dense seagrass beds (Carlson et al., 2018; Fourqurean and Roblee, 1999; Johnson et al., 2018; McIvor et al., 1994; Zieman et al., 1999). These conditions triggered a cascade of biogeochemical and ecological effects. Together with high temperatures, the hypersaline conditions caused hypoxic conditions and high levels of sulfide, which is lethal to plants (Koch et al., 2007; Rudnick et al., 2005), resulting in widespread seagrass die-off in the central and western portions of the Bay. The process is outlined in more detail in Figure 5-22. This series of events represents a collapse at the base of the food web, and the consequences included unstable sediments, algal blooms, and increased turbidity (Deis, 2011; Hall et al., 1999), with major effects on commercial and recreational fishing. Although the system recovered over a 20-year period, there have been environmental concerns since, including a second seagrass die-off in 2015; both events were similar in scope of near total mortality (over 90 km^2) and location (Figure 5-21). Ultimately, more than 160 km^2 were affected in 2015, and the cascade of ecological responses followed similar conditions as that in the 1980s—localized drought, high temperatures, and hypersalinity.

Ecological implications. Two large seagrass die-off events in recent history (beginning in 1987 and 2015) caused substantial ecological degradation, including widespread turtlegrass (*Thalassia*



This model has been developed to explain the causes of seagrass die-off in Florida Bay and is based on a synthesis of field data and observations and mesocosm experiments. It shows a cascade of stressors that eventually lead to asphyxiation of seagrass that causes a die-off. The cascade of events is stimulated by phosphorus P enrichment from the Gulf of Mexico that leads to high summertime productivity and high oxygen consumption O_2 in the system by both plants and sediment (sulfate reduction $SO_4^{-2} \rightarrow SO_3^{-2}$). Release of dissolved organic carbon DOC from the plants further stimulates sulfate reduction and accelerates oxygen demand by the rhizosphere (root system). During drought years in the summer, high temperature and hypersalinity NaCl increase the plants' requirements for oxygen in the water column. In the fall, day length shortens, temperatures cool, and plants produce less oxygen O_2. The peak of the hurricane season in September introduces freshwater to the system, and epiphytes cover seagrasses. Nighttime hypoxia occurs at the sediment-water interface, creates an oxygen imbalance in the system, and results in plant asphyxiation and toxic sulfides H_2S accumulate in organic carbonate sediments that are low in iron. Plants die due to exposure to poisonous hydrogen sulfide. Although die-off can be extensive, seagrasses have been shown to recover. Live shoots are still present and those plants and new recruits can fill in open spaces in about 10 years. The increasing frequency and earlier seasonal occurences of die-off events are a recent concern.

FIGURE 5-22 Conceptual diagram of the causes of seagrass die-off. SOURCE: Kruzynski and Fletcher, 2012. Reprinted with permission; copyright 2012, Ian Press /University of Maryland Center for Environmental Science.

testudinum) mortality (Figure 5-22). The first die-off was notable in multiple ways: the speed of weeks to months, affecting *Thalassia* only at a large spatial scale, with small-scale patchiness, reticulated distribution, and sharp transitional boundaries (Hall et al., 2016). A multiyear drought followed this event, and a cascade of ecological effects was documented. Widespread and persistent blooms of cyanobacteria (*Synechococcus* sp.; Berry et al., 2015; Glibert et al., 2009; Phlips et al., 1999) and widespread turbidity due to resuspended sediments coincided with large-scale decimation of sponge communities, causing loss of critical nursery habitat for important commercial species, including spiny lobster (*Panuliris argus*) and pink shrimp (*Penaesus duoranum*) (Fourqurean and Robblee, 1999; Butler et al., 1995; Peterson et al., 2006; Robblee et al., 1991).

Both events originated in the northern portions of the Central Florida Bay. Cole et al. (2018) found that basins with severe seagrass die-off in 2015, when sampled more than 2 years before, had higher total phosphorus concentrations and seagrass cover (dense, monotypic stands of *Thalassia*) than basins that did not experience severe die-off. Basins with severe seagrass die-off also had lower dissolved inorganic nitrogen (DIN) and a lower ratio of DIN to phosphorus, indicating that they were less phosphorus limited. These findings suggest the need for increased freshwater flows in the northern central regions of the Bay (e.g., Rankin Bight)—areas with dense seagrass supported by marine phosphorus inputs—to prevent hypersalinity events and reduce the frequency of future seagrass die-off events.

Improved volumes and timing of freshwater flows could also enhance the diversity of seagrass species, which could help strengthen the resilience of the Bay to future seagrass die-off events (Herbert et al., 2011). Seagrasses are sensitive to salinity. Changes in salinity regimes over the past several decades are thought to have contributed to a shift in seagrass species distributions (Fourqurean et al., 2003; Zieman, 1982). *Halodule wrightii*, a species that favors lower mean salinities and more variable salinity conditions than *Thalassia*, was the observed dominant species in much of north and northeastern Florida Bay prior to the 1970s, while *Thalassia* typically dominated the western part of the bay (Zieman et al., 1989). By the time of the late 1980s die-off event, north and northeastern Florida Bay were dominated by high-density, monotypic stands of *Thalassia*, which are considered the most vulnerable to die-off events (Hall et al., 2016). Return to a mixed species composition may also support higher fish densities (Chester and Thayer, 1990; Thayer et al., 1999).

Restoration Goals and Expected Near-Term Effects of CERP Projects

In light of the seagrass die-off in the late 1980s and early 1990s (Zieman et al., 1999), the CERP aimed to increase overland flow into Everglades National Park and Florida Bay to improve salinity conditions. The broad CERP goals related to Florida Bay are captured in the 2007 Interim Goals Agreement (USACE et al., 2007):

- Increase freshwater flows to Florida Bay;
- Reduce the intensity, duration, frequency, and spatial extent of high-salinity events, reestablish low-salinity conditions in mainland nearshore areas, and reduce the frequency of and rapidity of salinity fluctuations resulting from pulse releases of freshwater from canals;
- Minimize the magnitude, duration, and spatial extent of algal blooms in Florida Bay;
- Reestablish a diverse seagrass community with moderate plant densities and more natural seasonality, and increase the percentage of Florida Bay having suitable habitat for seagrass growth;
- Increase densities of juvenile shrimp within the various basins of Florida Bay; and
- Increase the frequency of salinities less than 20 parts per thousand in the northern enclosed sub-basins of Florida Bay to foster optimal growth and survival of juvenile crocodiles

Yellow Book projections for Florida Bay. Collectively, CERP projects, including new southern sources of water storage in the Lake Belt, were expected to "improve the salinity regime in the coastal basins adjacent to Florida Bay" (FWS, 1999). However, scientists and planners did not have reliable flow estimates from the CERP to Florida Bay, due to the coarse (2 mile x 2 mile) grid size used by the South Florida Water Management Model and the difficulty of accurately simulating flows near the coasts. Since the CERP was launched, extensive research has led to a broad scientific consensus that wetter conditions prevailed in the historic system than previously thought (McVoy et al., 2011; NASEM, 2016). Restoring predrainage conditions in the Everglades and Florida Bay would require substantially greater water depths, flow volumes, and flow velocities than assumed in the Yellow Book (Marshall et al., 2020; RECOVER, 2011a).

Expected effects of planned CERP projects. Two currently authorized CERP projects—CEPP (including the EAA reservoir) and the C-111 Spreader Canal (Western) Project—affect Florida Bay. Modeling for the RECOVER Interim Goals analysis shows that, collectively, these projects are expected to increase surface-water flows to Florida Bay (across the T23 transect [see Figure 5-23]) during the dry season by 50 percent (or 28,000 acre-feet) (RECOVER, 2020b). During the wet season, flows are slightly reduced (by 3,000 acre-feet). Although this is not a large increase in average flow on an annual basis (11 percent) and far below predrainage flows, these discharges are expected to reduce salinity in nearshore basins, particularly in North Florida Bay (Figure 5-19). This increase in flows is expected to lead to a decrease in annual mean salinity of 1.4 and 2.8 ppt in Little Madeira Bay and Terrapin Bay, respectively, with comparable reductions in 75th percentile salinities. USACE and SFWMD (2014) noted that CEPP represented a 12 percent improvement toward the full restoration salinity target (Figure 5-24). The addition of the EAA reservoir to the CEPP project showed relatively minor effects on Florida Bay, with an additional 7,000 acre-feet per year above CEPP, with a corresponding limited decrease in salinity of 0.05 PSU (USACE, 2020a). Part of the reason such little benefit is seen from the EAA reservoir is that equivalent seepage management was not included in the project to facilitate conveyance to the south without exceeding flood constraints. Southern Everglades is a future CERP planning initiative that will include several project components from the Yellow Book that could benefit Florida Bay if implemented, including ENP Seepage Management, Lake Belt Storage, and Lake Okeechobee ASR. The planning process for southern Everglades is scheduled to begin in 2023 (USACE, 2020c).

As discussed in Chapter 4, the Combined Operational Plan (not included in the Interim Goals modeling) is projected to increase freshwater flows into Florida Bay by 36,000 acre-feet per year, which

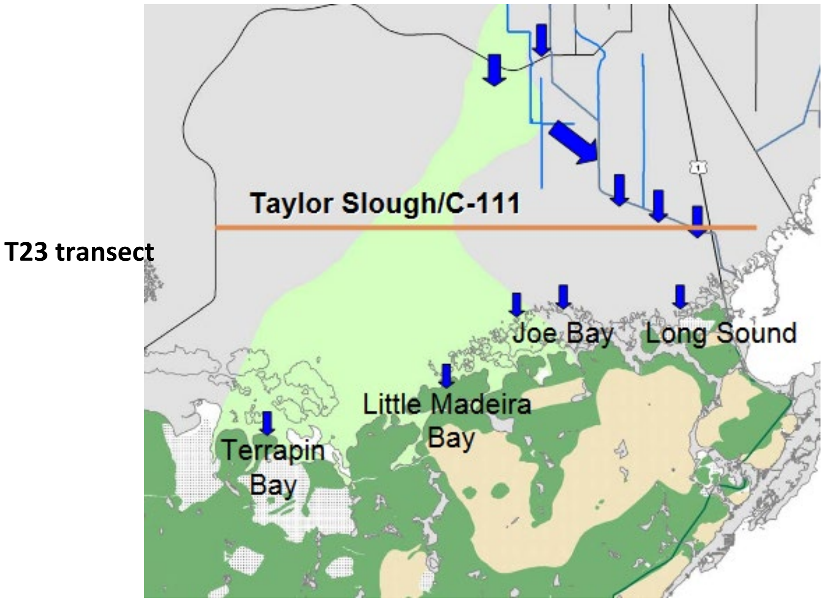


FIGURE 5-23 Location of the Taylor Slough/C-111 (T23) transect for flow into Florida Bay. SOURCE: DOI, 2009.

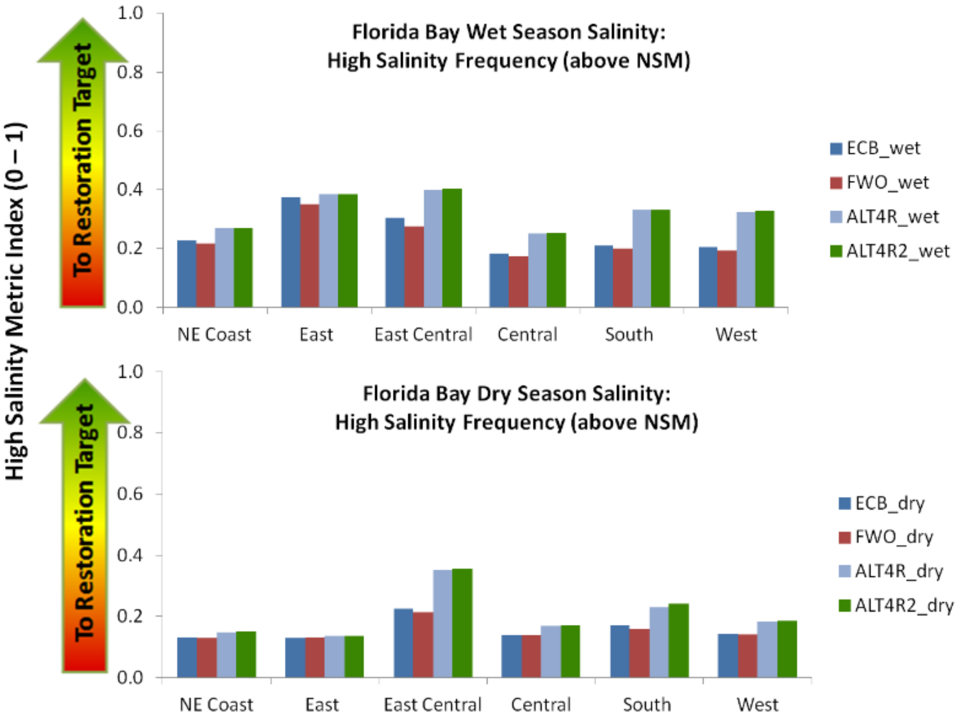


FIGURE 5-24 Effects of the CEPP plan (Alt4R2) on the high-salinity performance measure for different regions of Florida Bay. Conditions generally remain poor relative to the restoration target based on the natural system regional simulation model. SOURCE: USACE and SFWMD, 2014.

is greater than that projected from CEPP and the EAA Reservoir. The greatest increases in overland flow occur through the Eastern Panhandle to East Florida Bay.

Implications of Environmental Issues for CERP and Non-CERP Efforts

The CEPP and the C-111 Spreader Canal (Western) project provide most of the Florida Bay salinity benefits to the East Central Florida Bay (Figure 5-24) through increases in Taylor Slough flows. The COP also provides most of its benefits to East and East Central Florida Bay. The benefits, however, are relatively modest compared to predrainage flows. Restoring predrainage flow to Florida Bay is not a realistic expectation given the massive reduction in natural water storage in the Everglades ecosystem, and therefore it is even more important to understand the spatially explicit benefits to Florida Bay of the water that is delivered. Given the size of Florida Bay and its restricted circulation, increased CERP flows to only the eastern and east-central portions of the Bay will likely to have limited effects on salinity on Central and West Florida Bay. Yet, the two notable seagrass die-off events started in the Central Bay (Figure 5-21), where dense seagrass beds exist and mud banks significantly limit circulation—conditions which are essential to a die-off event. Additional efforts beyond the current authorized projects, either within or outside of CERP, would be needed to meet CERP's goals for Florida Bay related to hypersalinity events, seagrass, and algal blooms.

Key Questions to Inform Management Decisions in Florida Bay

Much research has been done to investigate the role of freshwater flow in the environmental problems of Florida Bay and to utilize a combination of monitoring and modeling to quantify how CERP projects will impact freshwater delivery relative to flow and salinity targets. However, Florida Bay is influenced not only by this freshwater inflow and its inherent water quality but also by the Gulf of Mexico; both hydrologic drivers will change in the future as a function of global land use and climate change. Given the size of public investment in restoration, as well as the emergence of new challenges since the CERP was first envisioned, adaptive management of the CERP will be critical to meeting restoration goals for Florida Bay. This requires the identification of key questions central to addressing problems that need to be addressed to develop appropriate management responses. Examples of questions relevant to Florida Bay management decisions are provided in Box 5-8.

BOX 5-8 Key Questions Relevant to Florida Bay Management Decisions

1. **What are appropriate spatially explicit, resilience-based restoration objectives for Florida Bay?**
    - Seagrass die-off events represent an ecological tipping point that results from a variety of factors: temperature, salinity, seagrass community composition, productivity, and nutrient status. Where and under what conditions are these tipping points of greatest concern? Can these tipping points be predicted in a spatially and temporally explicit manner?
    - What water deliveries are necessary to support the avoidance of die-off events, or the recovery from such events, in a spatially explicit manner? How will different levels of increased flows and/or distribution of flows affect ecological conditions in Florida Bay?

2. **How can CERP and non-CERP water management projects be optimized to make more progress toward these objectives and significantly reduce hypersalinity and seagrass die-off events?**
    - How can more water of sufficient quality be conveyed to Florida Bay and southwest coastal wetlands?
    - How can water be conveyed to north central Florida Bay to decrease hypersalinity?
    - How can seepage losses be further reduced from eastern ENP? What is the impact of additional seepage management on restoration objectives for Florida Bay?
    - What are the implications for Florida Bay if the CERP Lake Belt storage projects are never implemented?
    - What are the larger-scale trade-offs between increasing flow to western Taylor Slough from Shark River Slough (assuming this is feasible)? For example, it should not be interpreted that water is needed less in Shark River, and thus should be diverted eastward, for resiliency of Florida Bay, since the maintenance of Shark River flow is necessary for protection against peat loss.
    - How does the timing of restoration actions affect what is achievable?
    - What are the trade-offs between increasing flow to Florida Bay and restoration of Biscayne Bay?

3. **How can water management foster greater ecological resilience in light of climate change and sea-level rise?**
    - How will sea-level rise, ocean acidification, and temperature increase interact to impact the Florida Bay ecosystem (water and nutrient budgets, peat loss, carbonate mud bank stability, ecological function) and what is achievable from CERP in Florida Bay?
    - What are the freshwater inputs necessary to maintain strategic ecological functions?

Science Support for Restoration Management Decisions in Florida Bay

A long history of research has led to a robust understanding of the changing ecological status of Florida Bay and its causes. However, current restoration efforts are proceeding under conditions that are changing rapidly toward a future with uncertainty, and a new set of tools is necessary. Monitoring and research, syntheses, and modeling could be used to address the key questions posed above under these new conditions; these new tools would include a refined set of ecological expectations, quantitative understanding of spatial trade-offs between various flow management approaches, methods to operationalize decisions, and support of long-term regional planning and coordinated management actions among CERP and non-CERP efforts. The status of these tools, as they apply specifically to Florida Bay, are reviewed in the following sections.

Biological effects monitoring, synthesis, and modeling. Florida Bay has been the focus of a range of scientific inquiry efforts by both agency and academic personnel, with remarkable progress via causal investigations linking biological outcomes, such as seagrass communities and alligators, to environmental drivers, principally freshwater flow. Multidisciplinary investigations of the drivers and causal relationships behind the first massive seagrass die-off in Florida Bay is an excellent example of a living science model, where two decades of monitoring, experiments, and modeling research supported by Alligator Alley toll funds, RECOVER, and competitive federal grants in combination with the multiagency Marine Monitoring Network iteratively identified the interplay of five causal factors contributing to this die-off and subsequent recovery trajectories: upstream discharge, hypersalinity, high water temperatures, low wind speeds, and low dissolved oxygen (Figure 5-22; Johnson et al., 2018; Rudnick et al., 2005; Zieman et al., 1999). It was also recognized that the shift in seagrass community composition since the 1960s—from mixed species stands to *Thalassia*-dominated, dense, monotypic stands (Fourqurean et al., 2003; Zieman, 1982)—increased vulnerability to the initiation of die-off events.

This level of understanding allowed the development of two ecological models that link salinity and other drivers to seagrass die-off and community structure: the Florida Bay Seagrass Community Model (SEACOM; Madden and McDonald, 2006, 2007) and a statistical discriminant function model that assigns a probability of eight seagrass community types occurring for a given combination of water quality variables (Fourqurean et al., 2003; Herbert et al., 2011). While SEACOM is a physiological/mechanistic model (one that attempts to represent the interaction of multiple physical, chemical, and biological processes in real time), the second is a statistical model (based on demonstrated relationships between a suite of water quality parameters and the occurrence of various seagrass communities). The existence of both provides robustness to our understanding of seagrass community processes and represents an advanced capability for the type of ecological forecasting that is necessary for adaptive management of the restoration effort.

SEACOM is a process-based seagrass biomass unit model that was developed to capture the effects of freshwater inflows and hypersalinity, sea level, high water temperatures, low wind speeds, and low dissolved oxygen, which drive the production of sediment sulfides that are toxic to seagrass plants (Johnson et al., 2018). The model was developed to evaluate these mechanisms and their effects on seagrass community processes, distribution, and survival (Madden et al., 2016), thereby informing and improving coastal management of seagrass systems. The model currently includes fully integrated *Halodule wrightii* and *Syringodium filiforme* modules in addition to *Thalassia*, and a provisional *Ruppia maritima* module, calibrated for nine basins that represent a large part of Florida Bay. SEACOM has been used in a number of management decisions, utilizing the hydrology and water quality variables produced by another modeling effort, FATHOM, as input. Thus, SEACOM results could only be as spatially explicit as FATHOM results (54 basins covering Florida Bay). SEACOM model code will eventually be incorporated into a 3D regional ocean modeling system hydrodynamic/water quality model that will enable full spatially explicit simulation of seagrass dynamics across the Bay and at the sub-basin scale (C. Madden, SFWMD, personal communication, 2020).

A second seagrass ecological model links environmental drivers to seagrass species composition. Because seagrass species exhibit different sensitivities to salinity climates, models are available to predict potential shifts in seagrass communities with changes in freshwater flow expected under the CERP. Herbert et al. (2011) used salinity climates from the hydrodynamic model FATHOM as input to a statistical discriminant function model that associates eight seagrass community types with water quality variables including salinity, salinity variability, total organic carbon, total phosphorus, nitrate, and ammonium, as well as sediment depth and light reaching the benthos. This ecological forecasting is valuable in setting expectations for the restoration effort. Salinity climates in the western sub-basins were expectedly insensitive to modeled increases in freshwater inflow, while the north, northeastern, and eastern sub-basins were highly sensitive and exhibited predicted and favorable shifts in community composition (Herbert et al., 2011). It is notable that this second model also utilizes FATHOM as input, and thereby is limited in its ability to predict at a finer spatial scale. Thus, both seagrass models cannot be made spatially explicit without a hydrodynamic model that provides higher-resolution predictions than are currently available with FATHOM.

Florida Bay monitoring and research has also supported the development of other ecological models. A crocodile habitat suitability index, which characterizes the suitable habitat, based on observed salinities, nest sites, and prey biomass during periods in which hatchlings are the most vulnerable to high salinities (Brandt, 2013), was utilized to assess CEPP alternatives. A spatially explicit, stage-based population model has been developed and run for assessment of CEPP (Green et al., 2014). A habitat suitability model is also available for pink shrimp (Mulholland, 1984), and pink shrimp have been advocated as a performance metric for Florida Bay restoration (Browder and Robblee, 2009), although neither are currently used in restoration planning.

The tipping points associated with seagrass die-off events involve more than salinity. There was high spatial coincidence between the *Thalassia* die-off events initiated in 2015 and 1987, and hypersalinity, water column stratification, and bottom-water anoxia were again identified as major causal factors (Hall et al., 2016). Although the basic conceptual model is accepted, the climatic conditions that precipitate hypoxic stress within the densest meadows is still unclear and may involve a combination of several meteorological events that lead to increased evaporation or stratification in these precise areas. Conditions for recovery are even less understood; although almost full recovery from the 1987-1990 die-off occurred over the ensuing 20 years and followed paradigms of *Thalassia* succession (Hall et al., 2016), the conditions that supported it have not been characterized or summarized. Seagrass monitoring (Madden et al., 2009; RECOVER, 2007a) could be useful as early warning signals of vulnerability to die-off events as well as indicator conditions necessary for sustained recovery, allowing for improved operational decision making.

Hydrologic and hydrodynamic modeling and observations. The ability of ecological models to provide spatially and temporally explicit information to support decision making is constrained by the corresponding resolution of the data for the relevant environmental drivers. Direct and quantitative linkage of Florida Bay salinities—important forcing terms for seagrass and other ecological models—to southern Everglades freshwater deliveries has been problematic. Salinity is affected by upstream flows, evapotranspiration, precipitation, and circulation, and, therefore, spatially explicit salinity predictions require accurate models of surface- and groundwater inflows and bay hydrodynamics. Especially challenging is the ability to simulate surface-water and groundwater flows at the coastal boundary and their effects on the salinity of the North and northern Central Bay, where the CERP is expected to have the greatest potential impact.

Florida Bay hydrodynamic models (FATHOM and EFDC) and water salinity models (FATHOM) have been developed and validated by management agencies to support restoration conversations. However, these management-adopted models have not been fully integrated with upstream hydrologic drivers, and further model development and integration efforts are needed. Additionally, significant data gaps, such as uncertainty about the role of groundwater flow as a driver of Florida Bay response, require further investigation. Currently, in the absence of more explicit tools, CERP planning has relied on the use of multiple linear regression models (Marshall et al., 2011), which relate inland hydrologic variables (e.g., stage) and marine and weather data to predict salinity at 37 Florida Bay index areas. The models reproduce daily salinity simulations that are capable of estimating 65 to 80 percent of the daily variability in salinity depending upon the model; the models have little bias, but the absolute daily error in the nearshore embayments and the mangrove zone can be sizable during seasonal transitions on particular daily simulation. FATHOM in combination with multiple linear regression models to date has successfully supported management conversations on minimum flow (SFWMD, 2006, 2014) and CERP restoration planning discussions (USACE and SFWMD, 2014). EFDC is a 3D finite difference hydrodynamic model that was developed for Florida Bay through successive iterations in 2004 and 2008. EFDC was originally intended to be coupled to a water quality model to simulate factors that could affect seagrass die-off. The model development went through model validation stages but reportedly did not progress because of long run times and significant issues with the water quality module (Hamrick and Li, 2008). The original vision for the EFDC hydrodynamic model was to couple it with a biogeochemical submodel and link these to a coastal hydrodynamic model (SF-HYCOM; see Table 5-7) to provide Gulf of Mexico boundary conditions for the EFDC model, which would provide a mechanism to explore the effects of climate change, although these linkages were never completed.

Spatially explicit water and salinity budgets of Florida Bay have been challenging to construct, however, because the magnitudes, seasonality, and spatial distributions of southern Everglades inflows are poorly understood (Mills et al., 2019). Models that link the hydrodynamics of estuarine and coastal waters with coastal wetlands and watersheds remain insufficient to address fine-scale water distribution issues, groundwater–surface water exchange, saltwater intrusion, and the resulting effects on plant communities, soils, sediments, and biogeochemical cycles. Mills et al. (2019) noted that accurate predictions of salinity in northern Florida Bay requires moving beyond static stage-salinity relationships (Marshall et al., 2011) to linked hydrologic and hydrodynamic models. As discussed previously (see Biscayne Bay), the BISECT model (Swain et al., 2019) is designed to connect regional hydrologic models (e.g., RSM-GL) with hydrodynamic models using three-dimensional density-dependent flow modeling. BISECT (Swain et al., 2019) has been already used to begin investigating sea-level rise scenarios on groundwater and surface-water flows and saltwater intrusion. As in Biscayne Bay, however, the accuracy of the model is limited by the lack of monitoring data in some regions. Mills et al. (2019) note that "to properly calibrate such a model, a network of existing monitoring wells may need to be improved/validated and additional new groundwater wells may need to be strategically installed in ENP [Everglades National Park] to assess surface water, ground water and surficial water flows and volumes from ENP into the Bay."

In addition, there is a need for comprehensive scenario assessment modeling to support operational actions that could increase freshwater flow, especially into northern Central Florida Bay, where algal blooms have historically originated. For example, questions exist regarding the ability to increase surface-water flow and seepage through Buttonwood Ridge into northern portions of Central Florida Bay, which may require operations to convey water to western Taylor Slough, potentially when Shark Slough stages are high enough to overcome barriers to flow. Assessment of how much water can be recovered from seepage at the eastern boundary of Everglades National Park is also an outstanding issue that could be addressed with additional groundwater modeling.

Summary: Integrated Modeling for the Southern Coastal Systems

In the long term, an integrated modeling framework of coastal response for the entirety of southern Florida that describes the interaction of human activities and ecological response is desirable to guide restoration investments and inform evaluations of trade-offs. Such models are necessary to examine conditions that trigger tipping points for seagrass die-off events and enhance the recovery from those events. Because of the complex number of factors that have to co-occur both spatially and temporally (e.g., nutrients and chlorophyll concentrations, salinity, temperature, circulation, stratification), integrated monitoring and modeling is critical to identify actions that are necessary and appropriate to avoid these tipping points. Project and operations decisions also inherently weigh differential benefits for ecological regions (e.g., Shark Slough versus Taylor Slough, Biscayne Bay versus Florida Bay) and balance a range of objectives (e.g., restoration, flood control, water supply). Integrated modeling along the southern

TABLE 5-9 Criteria and Status of Monitoring, Research, Syntheses and Predictive Modeling Tools for the Southern Estuaries

Category	Criteria for Status of Scientific Components	Status	
		Florida Bay	**Biscayne Bay**
Integrated Hydrologic System Modeling	**Terrestrial hydrologic basin predictions** can capture links in the hydrologic cycle from northern everglades, WCAs, STAs and water resource operations (including impacts of climate change)	Advanced	Advanced
	Coupled freshwater–groundwater predications to estuaries and estuary hydrodynamic models: freshwater flows from surface and groundwater, ocean tidal forcing and water surface elevation, estuarine hydrodynamic water, salinity	Intermediate	Intermediate
Watershed and Estuarine Water Quality	**Watershed water quality** can simulate (as a function of external and internal drivers) temperature, total nitrogen and total phosphorus, dissolved organic and inorganic nutrients, and chlorophyll a	Early stage	Early stage
	Estuarine water quality: Ability to estimate/model salinity and mass balances of nutrients as a result of ocean and freshwater mixing, model the combined extinction of light from turbidity and chlorophyll a (primary productivity)	Intermediate	Early stage
Biological Models	**Seagrass:** Can predict physiological effects of temperature, salinity, light limitation (turbidity, water color and chlorophyll a), and substrate on seagrass biomass	Advanced	Intermediate
	Fauna: Spatially explicit models that provide quantitative estimates of habitat to target species and remediate local stressors within sub-basins or sections of the Bays.	NA	Early stage

NOTES: Status ranges from *emerging* (observation or science components not yet implemented to capture relationships between drivers and environmental problems), *early stage* (basic relationships observed and reported but data gaps that inhibit formulation of advanced predictive tools have not yet been addressed), *intermediate* (observations and research synthesized and preliminary predictive tools developed, more developments/refinements are needed), *advanced* (predictive tools validated and in routine use). STA, stormwater treatment area; WCA, Water Conservation Area.

coastal systems can provide consistent information to clarify the trade-offs between alternatives at a systems scale and improve decision making.

The effects of sea-level rise, ocean warming, and acidification are anticipated to increase over the next 50 years, further increasing the needs for spatially explicit, mechanistic hydrodynamic and biogeochemical models, coupled to biological models to inform CERP implementation and adaptive management. August maximum sea surface temperature has already increased by 1°C between 1985 and 2016, making the future viability of seagrass uncertain (Carlson et al., 2018). Circulation and nutrient supply from the Gulf will change with sea-level rise, requiring new or improved models for salinity and water quality prediction and cascading effects. For example, declining pH from ocean acidification can dissolve carbonate sediments with associated biogenic phosphorus, increasing phosphorus availability and seagrass biomass (Jensen et al., 2009), while increased warming and hypoxia can make high-biomass seagrass beds more susceptible to die-off (Carlson et al., 2018). Brackish and freshwater peat marshes are at risk of subsidence with saltwater intrusion, leading to an associated release of nutrients (Wilson et al., 2018); the importance and complexity of the response of this portion of the coastal landscape to sea-level rise was covered in NASEM (2018).

Changes in water management may be necessary to maintain the elevation of these coastal wetlands and prevent peat collapse conversion to open water (Mills et al., 2019). Integrated modeling tools can be used to examine strategies that increase hydroperiods in coastal and near-coastal wetlands and reduce the effects of saltwater intrusion or increase surface-water flows to areas at the greatest risk of seagrass die-offs. While South Florida hydrologic observations, synthesis, and modeling are relatively advanced, this toolkit has not been used to its full capacity to investigate the effects of climate change and its impacts on the human and natural ecosystem components of the Greater Everglades. A summary of the status of readiness of the toolkit is provided in Table 5-9.

CONCLUSIONS AND RECOMMENDATIONS

The CERP will help address freshwater inflow concerns in all of the estuaries but it is only part of the solution. CERP ecological restoration goals, particularly in the northern estuaries and Biscayne Bay, cannot be met if water quality and associated algal blooms, which are outside of the direct purview of the CERP, are not addressed. CERP projects primarily aim to improve hydrologic and ecological conditions in the estuaries by enhancing the volume and timing of freshwater inflows, thereby bettering salinity conditions. However, additional hydrologic restoration beyond those planned to date for the CERP may be needed to meet stakeholder expectations for estuary recovery (e.g., reducing high-volume flows derived from local watersheds in the northern estuaries). Some CERP projects are expected to reduce nutrient loads, but the water quality components of CERP projects represent only minor aspects of the steps needed to meet water quality criteria in the estuaries. Requirements for compliance with the Clean Water Act to address pollution and water quality fall to the state and not to the CERP. Public expectations for improved estuarine conditions, such as healthy seagrass meadows, improved oyster habitat, and control of harmful algal blooms, extend beyond what the CERP alone can achieve and require both CERP actions and water quality and habitat improvements through non-CERP efforts. CERP planning has not rigorously considered the potential impacts of impaired water quality on its ecological goals. Understanding the collective impacts of hydrology and water quality in meeting restoration goals and stakeholder expectations is essential to support ongoing CERP and non-CERP management decisions. If the impacts of water quality are not well understood, CERP water management projects may be unfairly blamed for failing to meet expected outcomes.

CERP goals for the southern estuaries should be revisited and clarified in light of improved ecosystem understanding and modeling capabilities. Early formulations of the CERP had qualitative objectives for Biscayne and Florida Bays. Freshwater flow targets linked to spatially specific ecological goals were never developed for use in CERP planning because predrainage flows were not well understood and model predictions were poor along the coastal boundaries. For example, in Biscayne Bay, nearshore salinity goals were developed, but the absence of freshwater flow targets complicates an understanding of what is attainable. In Florida Bay, the authorized CERP and non-CERP projects (including the CEPP and the COP) do little to address the specific region where historic seagrass die-offs occurred. Analysis of ways to optimize CERP outcomes with available flows requires more spatially targeted goals for the region. Analysis of what can be achieved through the CERP is essential to manage stakeholder expectations and, if appropriate, motivate additional non-CERP efforts. Additionally, these analyses will facilitate evaluations of trade-offs in water use among other water users and other regions of the ecosystem.

Existing data and tools should be used to improve science support for decision making across the estuaries. The relevant agencies have a long history of monitoring, but existing modeling tools and data sets are underutilized. Models and monitoring data offer opportunities to rigorously examine restoration alternatives and constraints, better understand trade-offs, and develop management strategies to enhance restoration benefits.

CERP and non-CERP agencies will need an advanced set of predictive tools, developed and implemented through effective coordination among scientists and managers, to better support critical water management decisions ahead. High-priority science and modeling needs include

- Spatially explicit water quality models and a sustained program of observation and research to build toward a predictive harmful algal bloom modeling toolkit for the northern estuaries;

- Watershed loading and water quality models to predict effects of salinity, water quality, and light limitation on the viability of seagrass in Biscayne Bay;
- Spatially explicit and mechanistic biological models (e.g., seagrass, oyster), developed from appropriately scaled and sustained monitoring programs for the northern estuaries that can capture the quantitative basis for relationships between freshwater flows, water quality drivers, and biological outcomes of interest;
- Predictive tools to identify thresholds and tipping points in all the estuaries, such as the complex factors associated with algal blooms and seagrass die-off;
- A southern Everglades transition-zone observational and modeling program that supports project planning and can couple regional hydrologic models, including groundwater–surface water exchange, with spatially explicit estuarine hydrodynamic and salinity models; and
- Integration of modeling and observations across the entire southern inland and coastal system to evaluate cross-project synergies and ecological responses (e.g., the ecological response of Biscayne Bay and Florida Bay to enhanced seepage management).

Clarity in critical future water management decisions can help prioritize additional research, monitoring, modeling, and synthesis efforts to better support CERP and non-CERP initiatives. Open communication and cooperation between subregion research, observational, and model development teams are needed to facilitate improved model coupling, accelerate knowledge gains, and allow models to collectively address trade-off decisions. Advancement in modeling could benefit from improved coordination across the estuaries to accelerate knowledge gains and allow broader regional approaches to address trade-offs in decisions.

Climate change and sea-level rise will have major effects on the estuaries, and those effects need to be better understood to inform management decisions and develop strategies that will provide long-term restoration benefits. Terrestrial hydrologic monitoring, synthesis, and modeling in South Florida are relatively advanced, but this toolkit has not been applied to investigate the effects of climate change on the human and natural systems of the South Florida Everglades and associated estuaries. In the northern estuaries, estuarine hydrodynamic modeling is advanced, but in Florida Bay and Biscayne Bay, improvements to these modeling capabilities are needed. Improved modeling of coastal boundaries is required to understand the implications of sea level rise on groundwater and surface-water inflows and saltwater intrusion. Additional research is needed to extend these climate scenario predictions from effects on hydrology to effects on water quality and ecosystems, such as the accompanying effects of saltwater intrusion on peat loss and subsidence. To ready the toolkit for this exercise, investments recommended above to make water quality and biological models increasingly mechanistic and spatially explicit will also serve to credibly predict impacts from climate change stressors. This information can then be used to examine the long-term performance of projects and identify possible adaptive management strategies or design alterations to increase ecosystem resilience.

6

Science to Support Decision Making

Science has always been at the core of the Comprehensive Everglades Restoration Plan (CERP). By embracing adaptive management as a key tenet of restoration implementation, the Yellow Book (USACE and SFWMD, 1999) and subsequently the Programmatic Regulations (33 CFR §385.31) recognized not only the importance of a solid scientific underpinning of the plan but a need for continual scientific and engineering information to support ongoing restoration decision making. The Committee on Independent Scientific Review of Everglades Restoration Progress has recognized advances in science, including monitoring, modeling, and synthesis, in previous reports (e.g., NASEM, 2016; NRC, 2007, 2014). In recent years (NASEM, 2016, 2018; NRC, 2014), the committee's recommendations have focused on science to support long-term planning and setting forth realistic expectations of the future condition of the system. Yet, this is just one way that science can and should inform decision making. As the CERP and related programs come to fruition and critical pieces of the long-envisioned restoration infrastructure begin operations, new opportunities emerge for the application of existing knowledge and the development of a deeper understanding of system function and ecosystem response to water management.

Two non-CERP efforts—the Combined Operational Plan (COP; see Chapter 4) and the Lake Okeechobee System Operating Manual (see Chapter 3)—represent current large-scale examples of the potential utility of applying scientific information to inform operations. Scientific analysis in support of the COP used hydrologic and ecological models to evaluate alternatives and, to the extent possible, manage trade-offs across the system. As more information becomes available and models are improved, the operational plans can be refined through adaptive management to better meet ecosystem and other objectives. Because of the scale of the effect of the COP and the Lake Okeechobee System Operating Manual, systems-scale thinking and analysis has been essential (Box 6-1).

BOX 6-1 The Importance of Systems Thinking to the CERP

The CERP has impacts at a larger scale than individual projects, as one project component can have implications for other parts of the Everglades ecosystem. Changes in water flow and distribution can affect habitat quality and biogeochemistry, which could affect species populations in the project area with implications to other species and broader downstream areas. Water management changes also have important implications for water supply and flood control under typical and extreme weather conditions. Effective support for restoration decision making involves careful and transparent consideration of options, taking into account effects in one area relative to other areas and trade-offs, interactions, or synergies across the system, necessitating systems analysis (i.e., analysis of the whole system, rather than its individual parts in isolation). Systems analysis leverages understanding of the individual components by linking them together in a way that represents the best understanding of the components' actions and reactions to various stimuli. Systems analysis has been employed extensively for the CERP in the evaluation of individual projects. In the U.S. Army Corps of Engineers (USACE) project planning process, systems thinking is applied in the evaluation of trade-offs that examine various alternatives using modeling tools to identify a plan that meets the project objectives within existing constraints in a cost-effective way. Systems analysis can also be used to manage the Everglades system in accordance with new information arising from monitoring, and evolving understanding of the system and the challenges it faces.

The value of systems analysis extends far beyond individual project planning, and becomes even more important as the program pivots from a focus on planning and advancing individual projects toward operations and adaptive management of the partially restored system, in parallel with ongoing planning for the remaining CERP projects. Despite the need to consider project interactions and changing conditions, it is not clear that a systems approach is commonly used in other dimensions of CERP decision making as a way of applying available knowledge and scientific information. Maintaining a systemwide perspective was part of RECOVER's original mission (see Box 2-1), but realignment of responsibilities and the need to support project planning has greatly reduced the capacity of RECOVER to support systemwide learning and synthesis throughout the CERP. As a result, decision makers are forced to take actions without the full support of available tools and information to guide their decisions.

The committee identified four examples of ongoing or forthcoming decisions that can benefit from more refined, nimble, and logically consistent application of available science:

1. **Integrated project planning and scheduling.** The Integrated Delivery Schedule (IDS; see Chapter 3), which involves the scheduling of CERP and non-CERP projects, represents an example of a complex balance of trade-offs. Presently these appear to be driven more by progress on project planning and authorization than their contributions to overall system performance. Systems analysis could be applied in the development of the next IDS by evaluating alternative project implementation schedules over a number of scenarios of key external factors (e.g., state and federal funding levels), using a set of performance metrics representative of the multiple CERP objectives. Doing so would ensure that the schedule of projects is purposeful in terms of meeting future objectives by ensuring those projects that make a difference at the system scale are prioritized.
2. **Assessment of restoration outcomes and adaptive management**. A project-level adaptive management process (RECOVER, 2011b) has been crafted to support decisions on when or how CERP projects or project components need to be adjusted based on monitoring data to optimize their benefits. The outcomes of some CERP projects may be limited by factors outside the control of the CERP (see Chapter 5), making within-project adjustments and adaptive management less successful than expected. Understanding project-level and systemwide responses and their interacting causal factors through data analysis and modeling is essential to support timely decisions that can improve overall restoration outcomes. If the effect of actions on the system cannot be accounted for, adaptive management is impossible.
3. **Near-term operational decision making**. Although major operational changes, such as the COP (see Chapter 4), involve a lengthy planning process with structured evaluations of systemwide effects, CERP agencies face many other near-term operational decisions, such as those resulting from adaptive management or those involving extreme events. As more projects come online, operational decisions will be more complex, and these decisions, including operational changes, will benefit from tools and strategies that can efficiently and actively bring science and systems-level understanding to bear on near-term decisions.
4. **Science planning and investment**. As the system changes due to CERP implementation and other factors, CERP agencies will need to identify and prioritize the science needs to support future management of CERP infrastructure. Until now there has been little opportunity to consider how science in support of the CERP should evolve in the future. Ongoing research on issues such as peat collapse and the effects of sea-level rise (see NASEM, 2016, 2018) demonstrate that, as the system changes, science in support of the CERP should itself adapt. Decisions on the highest priority investments would be best informed by a systems-level perspective considering which information can add value to restoration progress.

Informing these decisions requires focused and deliberate application of science, and the Everglades restoration community has built a solid foundation of monitoring data and models. The long-awaited evolution of the program toward implementation and operation of multiple projects, however, requires a different kind of application of this toolkit of monitoring, modeling, and synthesis. In this chapter the committee explores how new strategies can improve the development of science to inform decisions and stimulate the systems perspective long envisioned. It will also examine key elements that support the use of science, once that science has been developed.

DEVELOPING THE SCIENCE AND SYNTHESIS TO INFORM DECISIONS

Scientific information and its application to restoration can take many forms. The complexity of a system like the Everglades requires detailed measurements and understanding of small-scale processes that are meshed with landscape-scale dynamics and regional factors such as meteorological and climate variability. Findings need to be captured in ways that support decision makers and foster learning about the restoration process by all involved. In this section three key scientific tools are described: monitoring, modeling, and synthesis. For each, the committee briefly summarizes the current status and then identifies strategies that can be used to further the development and application of relevant and timely science for each tool.

Monitoring to Inform Decisions

Current Monitoring and Assessment to Support Decision Making

The CERP Monitoring and Assessment Plan see NASEM, 2018; NRC, 2004; RECOVER, 2006, 2009) guides the collection of an impressive array of data on hydrology, water quality, and key ecological components, such as vegetation, wading birds, alligators, and oysters (Figure 6-1). These data are used to determine whether changes are occurring as a result of ongoing disturbance or restoration projects and to track performance measures. Every 5 years the System Status Report (SSR; see Chapter 3) provides regional analysis of the status and trends of different ecological attributes relative to identified targets for each attribute. Monitoring data are also collected specifically for each CERP project to evaluate progress and support adaptive management (see Chapter 3). Additionally, monitoring data are used to calibrate and validate hydrologic models and to develop response relationships for use in ecological and water quality models.

The ongoing data collection effort is impressive, but the program is failing to meet its potential. The value of data sets can be limited by lack of an analytical design targeted at the information most needed by decision makers. For example, the COP Adaptive Management Component, which demonstrates the utility of monitoring data for operational decisions, is being supported with existing monitoring (see Chapter 4). Existing monitoring designs intended for assessing general status and trends may not be sufficient to answer specific questions. In the northern estuaries, an improved, intensive seagrass monitoring program was initiated in 2018 to better inform predictive models that support estuary management decisions (see Chapter 5).

For the adaptive management to be effective, it is necessary to ensure that the data collected are adequate to address the highest priority questions. NASEM (2018) concluded that improvements are needed in the design of monitoring plans and that the ways data are analyzed can limit their usefulness. Furthermore, project-level monitoring varies in effectiveness (Chapter 3; NASEM, 2018).

Enhancing the Value of Monitoring

Monitoring typically falls into one of two categories: surveillance and targeted. Surveillance monitoring focuses on the status and trends of a system, while targeted data collection focuses on scientific hypotheses or management-related questions (Nichols and Williams, 2006). Targeted monitoring in a management context is connected to decision processes, which recognize the connections between objectives, potential management actions, models of response, confidence in models, and the monitoring program. The motivation for monitoring in the CERP is to meet both purposes, but, to do that

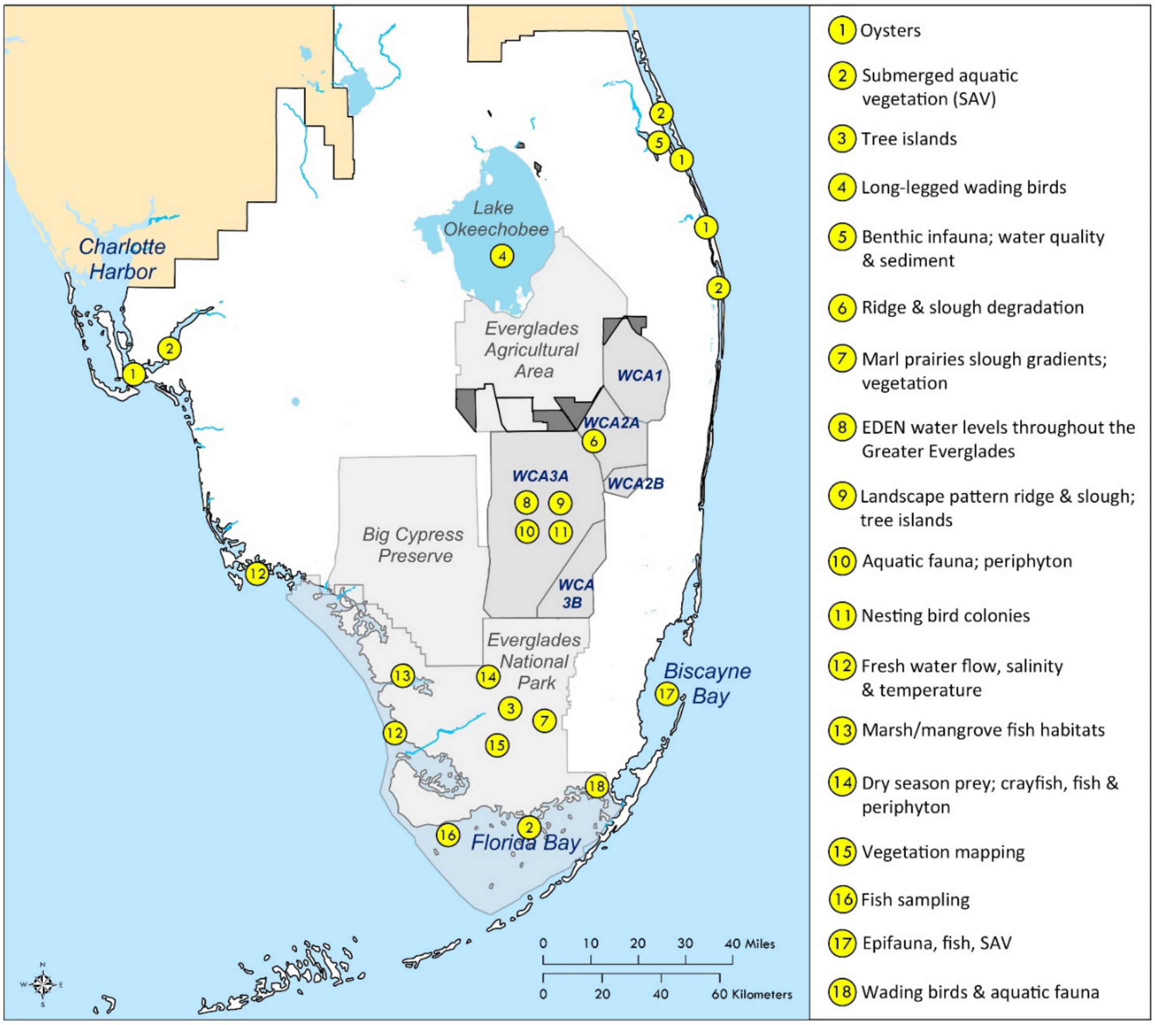


FIGURE 6-1 CERP systemwide monitoring plan. SOURCE: Adapted from A. Patterson, USACE, personal communication, 2017.

effectively and inform decisions, monitoring should be specifically designed with the decision(s) in mind. Monitoring may need to be modified over time as responses to restoration are identified, new management questions arise (or some former questions no longer need to be addressed), and issues not previously anticipated need to be tracked.

One way to substantially improve the value of monitoring for decision makers is strategic monitoring design. Decisions will be best supported when monitoring plans are designed to address key management questions (e.g., will operational changes better allow the project to meet its goals?) in light of natural variability and sampling constraints (NASEM, 2017). Models can be used to optimize the design of monitoring station placement and gauging station density, as well as the adequate temporal frequency of field observations (Baker and Culver, 2010; Mclaughlin and Graham, 1986). Such an optimization process might lead to substantial cost savings for monitoring programs and could free up resources for other purposes, such as data analysis to answer critical management questions. Given the extensive resources directed toward project planning and support for construction design, assessing current monitoring in the light of decision needs can focus resources and ensure appropriate data are being collected.

Some of the best ways to improve the use of monitoring to inform decisions, however, are through improved linkage and integration of monitoring and modeling and increased focus on synthesis, including a strong data management system. These are discussed in the following sections.

Modeling to Inform Decisions

Status of Modeling Science in the Everglades

The use of models has been a key tool in the CERP, primarily for planning CERP projects. Model development has been combined with expert-level application in systems analysis to support large-scale project planning, such as the Central Everglades Planning Project (CEPP) and the COP. In such studies, the models are used to evaluate the predicted response of project alternatives on hydrology, water quality, and plant and animal abundance and distributions, typically using climatological conditions from a historical reference period. The results provide support for selecting among alternatives and thus achieving the optimal outcome. The modeling used for CERP planning is led by the Interagency Modeling Center, with additional modeling conducted by individual agencies.

Understanding of the relationships between processes that drive the outcomes of interest generally begins with conceptual models and then evolves with increased knowledge to increasingly refined mathematical models. The existing computational models represent the formalization of much of what is known about the flow and distribution of water and ecosystem response throughout the Everglades. There is currently a strong gradient in the degree of maturity, robustness, integration, and trust in results of models used for hydrology, water quality, and ecological modeling.

Conceptual understanding of hydrologic processes is mature, and mathematical models of hydrology are correspondingly robust. Hydrologic models used in Everglades restoration follow accepted approaches, with widely agreed upon modeling tools whose results are broadly trusted. However, there is a general lack of characterization of the errors and uncertainty associated with the models (see SFWMD, 2018e and USACE and SFWMD, 2014, Appendix G for prior efforts to propagate hydrologic model error through the decision process), and so the degree to which they should be relied on is largely unknown (see also Chapter 4). Uncertainties within complex multilayered numerical models can be large to the point of masking the system response to certain projects or actions. An additional challenge is that hydrologic models are commonly developed and implemented within specific geographic subregions of the Everglades system, resulting in a compartmentalized collection of models of individual subsystems.

Understanding of water quality processes is also advanced, albeit subject to much uncertainty at landscape scales. The adoption of water quality models in Everglades restoration is much less advanced and integrated than those used for hydrology, with several different approaches of varying degrees of sophistication and trust in use for different purposes. Simplified water quality models have been used for authorization and design of stormwater treatment areas (STAs), and watershed loading models have been used to develop total maximum daily loads in sub-basins within the Everglades (see Chapter 5).

The adoption and use of ecological models in Everglades restoration is less advanced and less integrated than the hydrologic framework discussed above, although the number of ecological models and connectivity with hydrologic modeling tools continues to evolve (NASEM, 2016).[1] Ecological modeling is increasingly important in planning decisions (e.g., CEPP [see NRC, 2014], COP [see Chapter 4]).

The modeling effort has many strengths—notably the interdisciplinary nature of the modeling enterprise, including coupled hydrologic and infrastructure modeling components linked to ecological models, as well as the use of innovative machine learning techniques. Advances continue to be made in modeling and the status of the different types of models described above is common in other systems. However, full integration of models across hydrology, water quality, and ecology (see Box 5-8) in the Everglades remains a challenge.

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[1] The ecological models are tracked at https://www.jem.gov/Modeling.

Using Models in New Ways to Support Restoration Planning, Implementation, and Operation

Although the use of models can be an effective approach for identifying the designs that perform best in the model versions of reality, the current usage also leaves open the question of whether the projects are well designed and selected for the conditions they will face. In addition, the potential (but largely unknown) differences between the model representation and reality raises the issue of how to evaluate project outcomes once they are implemented. Project benefits in planning that are described solely in a theoretical model future are difficult to compare with the current status of the system, which complicates general understanding of (and support for) project benefits and evaluation of actual outcomes. For example, if the results of a project differ from the modeled results, does that imply that the project is not performing as expected, or is it simply due to a gap in the model's representation of reality? Or is the model discrepancy due to a prevailing condition that was not evaluated in the modeling exercise (e.g., the precipitation and temperature conditions occurring in real time)? These kinds of questions become central as the CERP moves from focus on project authorization to operating and adaptively managing the projects as they are implemented.

Models could be used to answer these questions by expanding the potential use and benefit of modeling. First, models could be used to extend the reach of observations, using up-to-date conditions and data assimilation to provide a consistent representation of the state of the system with which to compare monitoring data and develop an improved understanding of the system. This approach could support adaptive management of CERP projects by providing the range of "expected outcomes" for a project and allowing detection of where outcomes are diverging from expectations, and thus require adaptive management action. Second, models could be used to understand the potential effects of external factors on restoration, such as sea-level rise and precipitation changes, which may in turn inform decisions related to the IDS and expectations related to restoration goals. In this section, these new modeling applications are discussed, which could enhance support for decision making.

Using models to extend the value of monitoring data. Currently, it is difficult to deduce the status of Everglades restoration goals despite the substantial resources devoted to monitoring. This lack of a system-level view impedes clear communication about restoration progress (see Chapter 3). Understanding the status of the system is naturally difficult for such a large complex system; a number of specific factors contribute to this difficulty. First, the Everglades is subject to the random variability of natural processes, including weather and climate variability as well as the variability of ecosystem responses. These conditions make it difficult to conclude whether observations are reflecting the effects of newly implemented restoration projects, are simply arising due to random chance, or are related to factors other than restoration. Second, the large number of variables being monitored and the multipurpose nature of those variables, including economic, ecosystem, wildlife, and hydrologic objectives, complicates a simple summary of the state of the system. Furthermore, an understanding of how progress in one area or objective may affect progress in other areas in terms of trade-offs or synergies is needed to better assess the nature of restoration progress.

Existing models, supported by monitoring, provide the means to improve understanding and communication of the current status and near-term trajectory of the CERP. Unlike field observations, calibrated and verified model outputs provide a continuous and consistent representation of the state of the Everglades. Thus, the existing models could be used to provide a model-based status of the Everglades restoration. This can be achieved by simulating the current state of the system as a function of the observed external forcings on an annual or semiannual basis. The integration of models and observations can be further enhanced by using formal data assimilation methods (e.g., Kourafalou et al., 2015; Loos et al., 2020; Oke et al., 2015). By assimilating point observations, models can be used to create a coherent spatial and temporal representation of the status of the restored system promoting understanding of ecosystem dynamics beyond that possible with monitoring alone, in essence, a "nowcast" (see Box 6-2). This creates the best possible information summary using both model output and observed data, potentially supporting multiobjective trade-off analysis to track current project effects and better understand and communicate the complex nature and status of the system. The creation of a near-real-time simulation or nowcast would allow experts a deeper consideration of the state of the Everglades and its response over the recent past to restoration actions, weather, and other external forces. The nowcast allows the articulation of status on all objectives in a consistent way, providing decision makers with a more holistic view of system response to management.

Use of models for performance assessment requires strong integration of models with observed data and also integration of modeling and monitoring teams. Members of modeling and monitoring teams may be separated within agency structures requiring a deliberate management approach to foster the interaction. As projects are implemented and data are obtained, frequent comparisons of the observed data and relative correspondence to model predictions need to be consistently made to enable reevaluation of model formulations and management strategies. With improved integration of modeling and monitoring staff teams, updated model predictions could also be used to design more effective and efficient data collection programs. It could also allow the identification of trade-offs, synergies, and interactions between objectives.

BOX 6-2 Nowcast: Assimilation of Models and Observations to Understand Current Conditions

Nowcast is a term for a prediction made of the present time or the near future. Nowcasting is useful where the density observations in either space or time are inadequate to provide a complete understanding of present conditions. Models can be used to fill in the gaps between observations and also provide estimates of other variables that are not directly observed but nonetheless constrained by observations.

Nowcasts range from simple regression models that link current conditions to the variables of interest, such as that used for water quality prediction in Lake Erie (Francy, 2009),[2] to more advanced methods that assimilate recent observations with models to create optimal estimates of current conditions. For example, nowcasting is used in the Gulf of Maine to predict harmful algal blooms (Figure 6-2),[3] and for fisheries management on the U.S. West Coast through real-time predictions of fisheries bycatch and target catch (Hazen et al., 2018; Scales et al., 2017).[4] The Terrestrial Observation and Prediction System[5] is an example of a framework for assimilating ground-based and remotely sensed observations with models for a variety of natural resource management and ecosystem management applications.

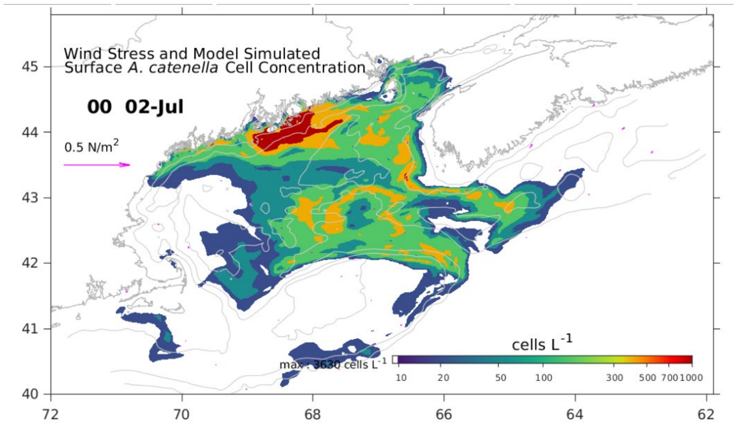

FIGURE 6-2 Model-simulated surface concentrations of *Alexandrium catenella* cells based on sea surface temperature, daily solar radiation, daily river discharge, 6-hour wind and heat fluxes, tidal forcing, and monthly nutrient data using a physical circulation model and a population dynamics model. SOURCE: https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-monitoring-system/gulf-of-maine-alexandrium-catenella-predictive-models/experimental-nowcast-forecast-simulation.

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[2] See Great Lakes nowcast at https://pa.water.usgs.gov/apps/nowcast/.

[3] See https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-monitoring-system/gulf-of-maine-alexandrium-catenella-predictive-models/experimental-nowcast-forecast-simulation/.

[4] See https://coastwatch.pfeg.noaa.gov/ecocast/.

[5] See https://software.nasa.gov/software/ARC-16197-1A.

The use of models for near-real-time simulation to better understand the effects of restoration projects can directly support adaptive management of those projects. At present, modeling to support project planning does not provide an expectation for project outcomes that can be compared with project monitoring. Without knowing whether observed deviations in project outcomes are due to the project or to external factors (e.g., anomalous rainfall), adaptive management is difficult. The effect of weather variability could be isolated from other factors by developing a set of stochastic weather time series that includes low-frequency variability due to the Atlantic Multidecadal Oscillation and the El Niño–Southern Oscillation and recent trends. It is also possible that this variability could be recreated by resampling of the historical record. This approach allows the isolation of the effect of the particular weather that year in comparison to the range of random weather that might be experienced. The uncertainty associated with natural ecosystem response is more challenging to characterize but if appropriate error distributions can be estimated (or assumed) this could also be incorporated within the analysis.

Using models in this way, as a strong tool for adaptive management, requires a new way of thinking commensurate with that associated with the move from project planning to system operation. Dedicating resources to a pilot application, jointly planned by managers and modelers, could demonstrate how the current use of models, based on historical hydrology, could be enhanced to understand how the system is responding to restoration efforts under current conditions.

The expanded use of models and observations represents a substantial effort and the benefits described here must be viewed in light of the cost of achieving them. The collection and processing of current boundary conditions is a significant effort in addition to the modeling runs themselves. Although near-real-time conditions may be difficult to achieve in the short term, more frequent updating of inputs and simulation of current conditions, for example, on an annual basis, would still provide improved ability to understand restoration progress from a whole system perspective. The potential benefits to the CERP are great through the improved decision making in planning and in operations that such understanding would yield. In addition, the approaches described here can be used to enhance communication of restoration progress to the public and political leadership, improving their understanding of the nature of progress and the need for commitment to restoration.

Using models to understand the implications of an uncertain future. Models could be central tools to assess future scenarios of environmental conditions or other external drivers, such as sea-level rise and precipitation changes, that affect the entire system (as discussed in detail in NASEM, 2018), but to date the focus has been on planning and implementing the backlog of projects. As projects come online and operations influence restoration success, assessing how external drivers influence interactions among projects could provide lessons learned to inform decisions related to the IDS and expectations related to restoration goals.

CERP models could be used to better understand the effects of changing external conditions on the Everglades and the implications of those effects for restoration. For example, a few studies have used a small number of scenarios representing changes in mean precipitation, temperature, and sea-level rise to drive hydrologic and ecological models to assess potential impacts on the Everglades system (e.g., Aumen et al., 2015; Nungesser et al., 2015; Obeysekera et al., 2011, 2015). The results indicate substantial sensitivity of the Everglades hydrology and ecology to the change scenarios, particularly the drying scenario (e.g., 10 percent reduction in average annual precipitation). However, because only a small number of possible futures have been considered, it remains difficult to deduce actionable information from the results. Given the difficulty of correctly predicting precipitation changes over the next 30 years, such analysis may have been viewed as speculative. However, working through plausible scenarios is an instructive way of anticipating potential adaptive management options in case more enduring climate changes happen (NASEM, 2018).

Recently a number of new methods for futures analysis, including vulnerability assessment, have emerged that focus on identifying ecological and water management tipping points and potential management responses (see Box 6-3). To better understand the implications of an uncertain future, RECOVER has initiated a vulnerability assessment. The ongoing vulnerability assessment is an example of how the CERP models that have been primarily used for project planning could be used to address the uncertainties of the future that threaten restoration success. However, it does not appear that the powerful modeling tools used for project development are to be used for this analysis. This would be a missed opportunity, since the models, as used in project development, are already configured to translate precipitation and temperature time series into hydrology variables and ultimately CERP objectives. Leveraging the incredible investment in these modeling tools to support vulnerability assessment ensures that outputs can be compared with planning results, and managers interested in restoration success can better understand what may lie ahead.

BOX 6-3 Vulnerability Assessment

A vulnerability assessment is a formal process to identify the vulnerabilities of a particular system or population (Glick et al. 2011; Hare et al., 2016; Williams et al., 2008). Turner et al. (2003) provides a reasonably useful definition of vulnerability as "the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress." Vulnerability considerations include the ability of a system to cope or respond, the scale of the system and hazard, and the heterogeneity of vulnerability levels possible within a system (e.g., different vulnerabilities for different parts or populations within the system).

With increasing interest in the vulnerability of systems and populations to climate change, general guidance is available for practical implementation of vulnerability assessment. First, the vulnerability analysis benefits from clear articulation of the objectives. As Brooks (2003) states, one "can only talk meaningfully about the vulnerability of a specified system to a specified hazard." The scoping generally involves the following framing:

- The system or population to be assessed (including the spatial boundaries),
- The measures or metrics or specific attributes by which the system vulnerability is assessed,
- The threat or hazard that potentially causes the vulnerability, and
- The time horizon for the analysis (e.g., present, near-future, or long-term future vulnerability).

Most vulnerability analyses emphasize the importance of stakeholder engagement for establishing the metrics for assessing vulnerabilities and thresholds on those metrics. Indeed, often the attributes of the system to be assessed and the measures used to evaluate vulnerability are defined via engagement with stakeholders who are knowledgeable of those attributes. In cases where separate stakeholder groups are defining thresholds it is important that they use a common concept for threshold setting.

Vulnerability assessments have been defined in both qualitative/quasiquantitative and quantitative methodologies. Qualitative assessments are based on expert judgment and have been used for biological vulnerability assessments. Quantitative assessments utilize computational models that represent a systems response to perturbation. The models can be used to simulate the effects of the threat or hazard by perturbing the models or model inputs in ways that represent the specified threat.

Methodologies for vulnerability assessment have also been described in terms of being conducted in a "top-down" manner or "bottom-up" manner. "Top down" refers to methods that place the emphasis on prediction of future conditions and understanding the vulnerability of the system to those expected future conditions. The concern with top-down approaches is that the use of predictions that are overly confident (meaning they underestimate the actual range of possible outcomes) could leave plausible vulnerabilities undiscovered. In addition, a common problem with top-down approaches is that when the number and range of future projections is overwhelming to practitioners, only a "best guess" or middle estimate is used. This will almost certainly underestimate vulnerability.

Bottom-up approaches, on the other hand, generally consider the future to be deeply uncertain, meaning prediction is beyond our current abilities. Instead, bottom-up approaches use carefully designed sensitivity analysis of the system itself. Thus the emphasis is placed on understanding the response of the system, rather than attempting to produce predictions of the future. Instead, vulnerabilities are revealed wherever the conditions cause them. This approach requires careful design of the sensitivity analysis to ensure interactions between factors are preserved or otherwise addressed.

Communicating and Reducing Model Uncertainties

Uncertainty is a topic that is central to modeling and decision analysis and yet often the bane of decision makers. However, model uncertainty is ignored at the peril of misinformed decision making and failed restoration. The difference between model output and field observations are the errors that define the predictive uncertainty of a model. Characterization of uncertainty in model results is essential for adaptive management of CERP projects; when the observations fall outside the predicted range, managers need to understand whether this is indicative of a problem in the project operations or design or whether the results can be explained by uncertainty in the model (see also Chapter 4). Characterizing and communicating model uncertainty helps to set realistic expectations for project performance and also allows improvement of the models themselves.

Quantifying and specifying the uncertainty of model predictions will help set realistic expectations for the results of restoration actions. In the current use of models for project planning, model results are typically presented as a single "best estimate" for the performance of each alternative over space and time for a given set of conditions. This best estimate of the effects of a particular project based on the modeling does not convey the range of possible outcomes based on both the uncertainty in the models and the difference between actual future conditions (e.g., precipitation patterns, climate) and the scenario(s) used to evaluate the alternatives. Figure 6-3 shows an example of how these differences may vary spatially. Uncertainty analysis conducted for the 2012 Louisiana Coastal Master Plan (CPRA, 2012) was conducted coastwide and by hydrologic basin (Habib and Reed, 2012). Although the coastwide values showed distinct differences between land area for Future Without Action compared to with the Master Plan projects in place, the effects of uncertainty in model predictions on land area varied by basin. In some basins (e.g., Lower Terrebonne), the uncertainty in model outputs was greater than the difference between model runs with and without the projects, while in others (e.g., Mid Pontchartrain), the modeling showed greater land area with the projects than without (Figure 6-3). Decision makers should be aware of uncertainty ranges, so they can understand the range of possible outcomes of restoration for any individual aspect of the system (which may include no improvement or worse performance in some cases for some objectives). In addition, a better understanding of uncertainty can help stakeholders and decision makers better understand the trade-offs between alternatives, which may be minimal for some objectives if the difference in performance between them is small relative to the uncertainty of the

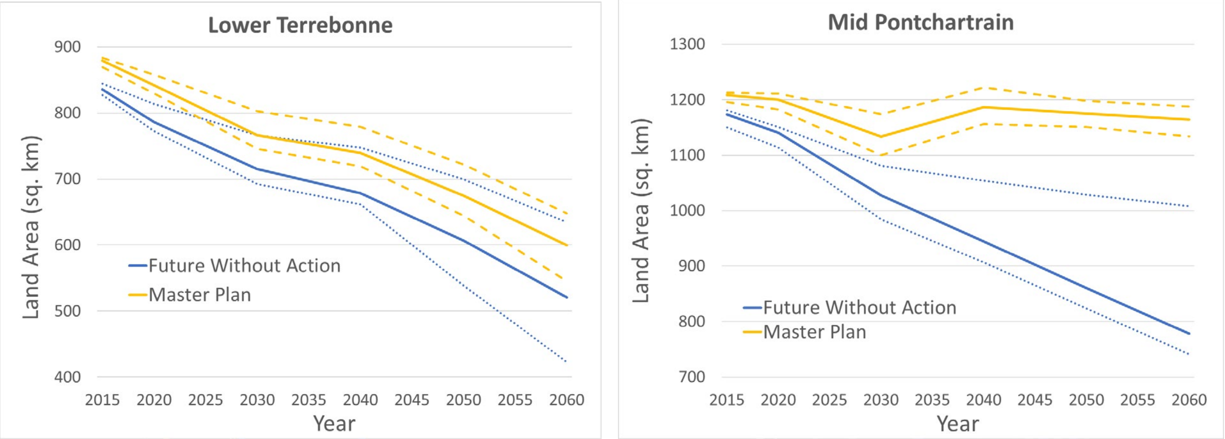

FIGURE 6-3 Temporal propagation of model uncertainties in land area predictions for two coastal basins under Future Without Action and with projects included in the 2012 Louisiana Coastal Master Plan. The displayed bounds represent the median (solid line) and the 10% and 90% percentiles (dashed lines). SOURCE: Data from E. Habib, University of Louisiana at Lafayette, 2021.

estimate. With communication of uncertainty, decision makers can also better understand the risks. For example, if the model estimate shows a slight improvement in an objective for a given alternative over the "Future without Action" scenario, but the range of possible outcomes includes significant decreases in this objective, decision makers should be aware of this possibility (Figure 6-3). Communicating uncertainty is not easy, but acknowledging and accounting for uncertainty is the only way to improve the robustness of decisions, both to modeling uncertainty and to the other contextual uncertainties (e.g., climate change, sea-level rise) under which Everglades restoration takes place.

Uncertainties in predictions produced by mathematical models can never be fully eliminated, but predictive uncertainties can be quantified and gradually reduced, with monitoring data playing a key role. The combined use of models with observational data in a continuous process of feedback and integration, termed "living models" (Loos et al., 2020; Orouji et al., 2013; Wang et al., 2016), can improve model performance and reduce model uncertainty. Field observations are typically used to set up, calibrate, and validate numerical models; living models use new observations to reassess and improve the parametrization and validation of the numerical tools. New observations can also be used in concert with the models to explore sources of variability and, thereby, help improve understanding of complex ecosystems. Sources of differences between observation and model outputs include (1) process stochasticity, or natural variation, (2) observation error, and (3) model structure errors (Harwood and Stokes, 2003). Identifying different sources of variability are important because stochasticity is not reducible, whereas other sources (such as parameter uncertainty) may be reducible with additional measurement (Rose et al., 2015). Model errors can potentially be characterized with a stochastic error function (e.g., Vogel, 2017) to provide a realistic prediction envelope for all model results. This in turn provides the best estimate of the actual range of effects predicted by the model.

Expanding the Use of Models

Models are generally used to support project planning and design, but there is currently little evidence of consideration of their use in subsequent stages of restoration, including performance assessment and design of monitoring programs. In particular, the 2020 South Florida Environmental Report (SFWMD, 2020) describes the use of modeling to support infrastructure project planning for the C-11 impoundment and improvement of canals and the use of water quality models for STA design and watershed management planning, but does not describe uses of modeling in the restoration operational and management phases of projects.

Modeling in the CERP to support decision making is built on the foundation of hydrologic modeling, but the regional hydrologic models used for the CERP are complex and cumbersome to set up and run. The limited access to and use of these regional modeling tools can act as the constraining step in broader use of modeling to support restoration decision making. Expanded capacity to run hydrologic model scenarios and interpret the results could support broader use of models overall, including ecological and water quality modeling. Broader application of models to decision making could be fostered through initiatives to expand the modeling staff and computing power and/or by extending the user base of CERP regional hydrologic models. The latter could include more coordinated and more formalized relationships between the Interagency Modeling Center and other partners, including cooperating agencies, universities, and nongovernmental organizations. Among the benefits of this would be the development of a stronger consensus about the underlying assumptions in each model and collaborative development of transparent documentation for each model.

Synthesis: Building a Knowledge Base

Synthesis enables science to develop a framework of understanding and more effectively inform management decisions. The National Research Council (NRC, 2010) defined research synthesis as "the process of accumulating, interpreting and articulating scientific results thereby converting them to knowledge and information." This remains a useful definition. Kemp and Boynton (2012) note a number of parallel trends and forces that motivate the need for improved scientific integration and synthesis. These include increase in the amount of scientific data and information produced "and their associated intellectual opportunities and burdens," interest in applying scientific knowledge for effective management, and the daunting complexity of recent environmental challenges. Synthesis can both increase understanding of the systems and minimize disagreements that sometimes hamper decision making. The RECOVER Programmatic Adaptive Management Plan (2015) also recognized the value of synthesis and called for development of synthesis on a number of issues including the need for freshwater delivery to the southern estuaries and the interaction of nutrient concentrations and fluxes on landscape and faunal restoration goals. In this section, the committee assesses ongoing synthesis efforts in the Everglades and discusses ways to enhance future synthesis.

Assessment of Everglades Synthesis

Previous synthesis as part of the CERP has included the development of conceptual models (Ogden et al., 2005; RECOVER, 2004) and the RECOVER Scientific Knowledge Gained document (RECOVER, 2011a). Conceptual models developed through the CERP provide a solid foundation for synthesis, but they do not appear to be widely used outside of identifying performance measures for project planning. Additional synthesis efforts have been conducted outside of the CERP, including some geographically focused efforts that have yielded substantial insights for ecosystem management (e.g., the Florida Bay Science Program [FWC, 2007], Marine and Estuarine Goal Setting for South Florida[6]). NRC (2012a) reviewed synthesis efforts that had been undertaken and recognized the magnitude of the effort, although some duplication was noted among the different synthesis products.

The only ongoing synthesis process is the RECOVER SSR, which has recently been produced every 5 years (RECOVER, 2007b, 2010, 2014, 2019). In the SSR, data sets and systemwide drivers, such as climate and sea-level rise, are discussed individually (see Chapter 3 for a detailed discussion of the 2019 SSR and the accompanying Report Card). Although the SSR informs the periodic Reports to Congress (USACE and DOI, 2011, 2016) and provides a useful compendium of data about different aspects of the system, it only provides a snapshot of current condition and fails to synthesize an overall view of how or why the system is changing. Moreover, it does not explain why degradation is particularly problematic in specific locations. Given that few restoration projects have been completed, it would be unrealistic to expect the 2019 SSR to provide an integrated view of restoration progress. However, the stovepiped approach to data presentation and interpretation provides limited insight on how cause–effect relationships propagate through the system. Although monitoring results for specific indicators provide valuable information, synthesis across indicators can be an effective mechanism for greater insight into system dynamics and ecosystem response. In commenting on the 2009 SSR, NRC (2012a) noted that "the effectiveness of the synthesis effort could be improved by explicitly addressing tradeoffs, conflicts, and commonalities among water quality, water quantity, and ecosystem responses." Such an integrated approach has yet to be adopted in the SSR. It is also unclear whether any of the decisions outlined at the start of this chapter utilize information presented in the SSR to change or adjust the way restoration, operations, or science planning proceeds.

Topic- or region-specific syntheses have been published that provide solid conceptual frameworks for understanding and communicating key scientific issues. For example, Chambers et al. (2019) documented the state of knowledge of peat collapse and provided insights into the long-term dynamics of parts of the system, and Douglass et al. (2020) synthesized submerged aquatic vegetation dynamics in the Caloosahatchee. Such benchmark overviews of available information and understanding can be used to underscore interpretation of monitoring data and model outputs, support adaptive management decision making, and guide investment to address priority science needs.

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[6] See https://www.aoml.noaa.gov/ocd/ocdweb/mares_reports.html.

Ways to Enhance Synthesis

Synthesis can take many forms. Data integration involves aggregating two or more potentially disparate data sets into an integral whole, typically to add new dimensions to the existing information or to address specific questions. Synthesis can also involve expanded and enhanced use of findings from different sources (e.g., distinct research disciplines, technologies, methodologies) in new contexts (e.g., through systematic review and meta-analysis). Conceptual synthesis bridges theories and paradigms that underpin previous studies.

For the CERP, integration and synthesis activities need to bring together not only monitoring program data, but data collected by others and relevant scientific developments in the Everglades and beyond. Conceptual synthesis tools for capturing current knowledge in a structured manner have been developed by the CERP (e.g., Ogden et al., 2005). This type of synthesis is a long-standing scientific practice. However, advances in computation and visualization techniques enable analytical approaches to synthesis that have been advanced through National Science Foundation (NSF)-funded synthesis centers at the National Center for Ecological Analysis and Synthesis (NCEAS) and the National Socio-Environmental Synthesis Center (SESYNC).[7]

Synthesis requires the application of disciplinary expertise and a systems perspective. Individuals who are good thinkers with considerable research experience and a good knowledge of relevant studies and system dynamics are needed, as well as those with skills in meta-analysis and other formal approaches to synthesis. Synthesis requires focus, and effective synthesis efforts typically require a strong commitment to its enterprise.

Given the level of effort involved in synthesis activities, the topics, scope, and periodicity need to be carefully considered and deliberately planned, targeted toward topics where synthesis could help the CERP move forward. For example, synthesis of research and data developed outside of the CERP on key issues (e.g., harmful algal blooms, nutrients [see Chapter 5]) can put CERP efforts in context. Over several years, and within the context of adaptive management and in support of CERP goals, a series of reports could be produced by experts in relevant fields for key issues (e.g., climate change, invasive species), subsystems (e.g., individual estuaries, Lake Okeechobee, STAs), or individual fauna (e.g., Cape Sable seaside sparrow) or landscape features (e.g., peat collapse). The concept is to go beyond the effects of an individual restoration project to consider emerging issues and how the system is changing and why. Insights would be gathered from available data and emerging research, and would draw in information generated by others (e.g., the Long-Term Ecological Research [LTER] program, university researchers, other state and federal agencies not directly involved in CERP). Several approaches to synthesis are highlighted in Box 6-4. These synthesis approaches build on available data and understanding to provide additional insight for use in project planning and restoration assessment, as well as other decisions.

The benefits of synthesis are worthwhile to pursue, and well-founded processes exist in the environmental science community. With a modest investment from the CERP and/or other parties, an ongoing synthesis program could be established that would be highly beneficial to CERP and allow for a broader understanding of natural resources in South Florida. One approach could utilize existing national synthesis centers (NCEAS or SESYNC) where staff skilled in different aspects of synthesis support synthesis projects and work with expert teams to develop synthesis products. Such an approach was used by the Bay-Delta Interagency Ecological Program, who worked with NCEAS to establish several workgroups to examine pelagic organism decline.[8] CERP decision makers, with input from RECOVER and the Science Coordination Group, could identify priority topics for synthesis annually and work with synthesis centers to support groups of scientists to work on specific synthesis projects. Via this process, science synthesis needs can be identified, prioritized, and provisioned on a timely basis for integration

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[7] See https://www.nceas.ucsb.edu/ and https://www.sesync.org/.

[8] See https://www.nceas.ucsb.edu/workinggroups/ecosystem-analysis-pelagic-organism-declines-upper-san-francisco-estuary.

BOX 6-4 Approaches to Synthesis

Kemp and Boynton (2012) note several approaches to synthesis that could be utilized to understand the changing state of the Everglades and the effects of restoration projects and operational changes:

- **Comparative cross-system analysis** uses similar data from different systems to assess how key attributes or processes vary in relation to differences in external drivers or other internal properties. This type of approach could be used to assess regional variations in response to drivers (e.g., effects of peat collapse on different coastal landscapes across the Everglades and factors exacerbating peat collapse).
- **Analysis of spatial and temporal data** is the foundation for the SSR and could be amplified, as described in Chapter 3, by multivariate analyses over longer periods.
- **Cross-boundary flux balances** could be developed systemwide or for subsystems for water and nutrient budgets or other parameters of interest. Water and phosphorus budgets have been developed for Lake Okeechobee, the Everglades Agricultural Area (EAA), STAs, and the Everglades Protection Area in the South Florida Environmental Reports (Julian et al., 2018). This approach could be expanded to include nitrogen or other contaminants.
- **Simulation modeling.** Mechanistic models can be used to simulate observed or expected patterns over space and time and for integrated analysis of various controls on ecosystem outcomes (e.g., physical, biogeochemical, ecological). Models can also assess tradeoffs among objectives (e.g., tradeoffs between ecological outcomes in Biscayne Bay vs. Florida Bay resulting from seepage management).

Although synthesis is not solely a data analysis exercise, ensuring an evidence-based case is important and leveraging available data and tools is crucial.

into the restoration effort. The model also has the advantage of not additionally burdening staff from the CERP implementing agencies to develop and lead the synthesis work on top of existing missions. With this model, one or two high-quality synthesis outputs could be produced per year that could be highly relevant to the needs of CERP.

Data Management to Support Synthesis

Everglades researchers have collected vast amounts of different types of data that potentially can be used in synthesis. Because the data and information span a wide array of temporal and spatial scales and are provided by different agencies and principal investigators, strong data management is required to support leveraging of these data to inform decision makers on the effects of restoration. Much has been written about the characteristics of a good data management system (NASEM, 2017). Especially relevant to data synthesis are the principles in the “FAIR system” (see Box 6-5) that are intended to strengthen the ability to reuse the data in future studies. Modern databases such as the NSF DataOne[9] and the Gulf of Mexico GRIIDC system[10] are examples of data management systems with a focus on establishing data legacy.

The need for good data management systems is well known within the CERP and among Everglades researchers. Several good relevant systems have been developed such as EDEN (developed by the U.S. Geological Survey for automated real-time water level data), DBHYDRO (developed by the South Florida Water Management District [SFWMD] for hydrologic and water quality data), and the Florida Coastal Everglades LTER database system (part of NSF DataOne). CERPZone is a multiagency collaborative environment connected to several data management systems to enable storage, retrieval, and

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[9] See https://www.dataone.org/.

[10] See https://data.gulfresearchinitiative.org/.

BOX 6-5 FAIR Principles

The FAIR principles are a set of guiding principles intended to improve the infrastructure that supports reuse of scientific data (Wilkinson et al., 2016). There are four foundational areas:

Findable: It should be easy to find data and metadata. Descriptors should be included to make data findable using search engines.

Accessible: It should be easy to access the data and metadata once it is located. Use a standardized protocol for accessing data.

Interoperable: The data that are in the database are in a consistent format with metadata to describe the collection process, study, and parameters associated with data quality.

Resuable: Sufficient information should be provided to allow the data to be used by other parties.

SOURCE: https://www.go-fair.org/fair-principles.

preservation of data and information relevant to Everglades restoration.[11] There are also useful databases that apply only to parts of the system, such as the Coastal & Heartland National Estuary Partnership (CHNEP) Water Atlas,[12] and other databases, such as the Watershed Information Network (WIN),[13] that focus on specific measurements.[14]

A renewed commitment by all participants in CERP data collection activities to developing metadata (i.e., the data that describe the observations and observation process), use of existing databases and associated standards, and timely uploads of new or updated data, can better support the program and utility of the data in synthesis. Data management and infrastructure should be designed and maintained with a long-term vision, so that data in the system are usable to future scientists who were not involved in the collection of the data. Data management requires a commitment from program managers, staff, scientists, principal investigators, and consultants to comply with (and enforce) standards related to when data should be added to the data management system, the form of the metadata, and the quality checks performed. Although it is often the role of the investigator or laboratory to check the data quality, random checks by the CERP Quality Assurance Oversight Team (QAOT) help to strengthen the application of quality assurance protocols.

Data quality and effective management can provide both short- and long-term benefits. A solid data quality program can increase a database user's time for analysis and interpretation and reduce the need for cleaning data. CERP's QAOT has focused on the quality of laboratory and field measurements associated with CERP projects through documents, presentations, and laboratory and field audits. QAOT (2019) includes evaluation of quality audits for several projects, including three CERP projects, with a focus on water measurements in DBHYDRO. The importance of noting quality-related qualifiers in the metadata are noted in Table 6-1 so that those who use the data for assessments understand the limitations of the data and can screen the data appropriately. Although quality assurance is critical to the CERP data and its use in informing decision, budget cuts have reduced communication programs and restricted audits (QAOT, 2019), limiting the effectiveness of the program. For example, biological data are currently not

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[11] See https://www.cerpzone.org/.

[12] The CHNEP Water Atlas covers several northern estuaries on the west coast of Florida, including Charlotte Harbor, Estero Bay, and their contributing watersheds. See https://chnep.wateratlas.usf.edu/.

[13] WIN is the Florida Department of Environmental Protection's repository of environmental data from nonregulatory data providers in Florida. See http://prodenv.dep.state.fl.us/DearWin/public/welcomeGeneralPublic?calledBy=GENERALPUBLIC.

[14] See also https://fcelter.fiu.edu/data/other-data-resources/index.html.

evaluated, and laboratory checks are only for SFWMD and USACE. The EDEN program, which is based on automated sensor systems, has data checks for their real-time data.[15]

Ready access to data without investing considerable time on cleaning and basic processing will allow it to be used in a more comprehensive and nimble manner. The recent Natural Resource Condition Assessment for Everglades National Park (Redwine et al., 2020) illustrates the considerable effort involved in assembling and synthesizing disparate data sets under the current system. The report was based on more than 100 data sets including GIS data, monitoring data, and information from publications. Although some data sets included metadata, they were often lacking in GIS data. The authors note, "The spatial scale of [the] EVER [Natural Resource Condition Assessment] makes assessment of data and synthesis among different resources more challenging, and it is this aspect of data summary that received the most effort by the NRCA ecologist." Automating the updating of databases can improve the turn-around time for analyses and synthesis reports and increase management response times.

TABLE 6-1 Summary of Water-Quality-Related Qualifiers from 18 Water Monitoring Stations in Picayune Strand

Water Year	Total No. of Data	No. of Quality-Related Qualifiers	Missing, Estimated, and Rejected Data			% Samples with Quality-Related Qualifiers
			Missing	Estimated	Rejected	
2013/2014	1,239,602	454,732	13,171	436,806	17,926	36.7
2015/2016	1,246,708	19,959	22,266	15,042	4,917	1.6
2017/2018	1,244,055	94,784	32,891	74,614	20,170	7.6

SOURCE: QAOT, 2019.

STRENGTHENING THE ORGANIZATIONAL INFRASTRUCTURE FOR SCIENCE SUPPORT FOR DECISION MAKING

As the CERP enters a new phase of implementation with increased focus on operational decision making (Chapters 3, 4, and 5), assessments of restoration progress (Chapter 3), and adaptive management in the face of changing conditions (Chapters 3, 4, and 5), the science infrastructure will also need to adapt to support these decisions. Overall, the effective use of science in decision making requires three things:

1. A process for the identification of science needs (in both the short and long terms);
2. The provisioning of those needs, including monitoring, modeling, and synthesis (discussed in this chapter); and
3. The integration of evolving science into decision making.

Although the processes for the integration of evolving scientific knowledge into CERP decision making may benefit from improvements, the committee did not examine that process for this report. There is already a rich literature on adaptive management and the processes to facilitate integration of science into decision making (e.g., Groves et al., 2019; Guerrero et al., 2017; RECOVER, 2011b). Instead, in this section the committee discusses the organizational infrastructure necessary to enable science support for decision making.

To provide adequate science support for restoration, CERP decision makers need a nimble organizational infrastructure, with skilled staff, freed from other responsibilities, to support ongoing monitoring, modeling, and synthesis and to facilitate effective communication of key findings with senior restoration decision makers. The need is already apparent. As discussed in Chapter 4, adaptive management for the COP alone involves extensive analysis of monitoring data to address identified uncertainties and inform managers of ways that the COP or other CERP projects could be improved to

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[15] See https://www.jem.gov/data/waterdepth.

better meet their objectives. The timeline of decision support for adaptive management and operational decisions will likely be shorter than the traditional 3-year project planning process and dispersed across many different projects, regions, and scales. The more nimble the decision process in adaptive management, the more quickly improved benefits can be realized.

The CERP envisioned the need for a structured approach to the integration of science and learning, and created the Restoration, Coordination, and Verification (RECOVER) program. RECOVER has specified roles in the assessment of monitoring data as CERP projects are implemented in support of adaptive management toward the systemwide goals of the CERP (see Box 2-1). However, with declines in staffing, RECOVER cannot meet the current demands for evaluation, assessment, and synthesis in addition to its own goals for keeping a systemwide, forward-looking vision, including vulnerability assessments and work on adaptive management (RECOVER, 2016). Recently, much of their staff time has been consumed by the needs of project planning as well as required reporting (e.g., System Status Report), with limited staff time dedicated to identification of science and monitoring needs to address changing conditions, systemwide modeling and analysis of ecosystem trends, or impactful synthesis. RECOVER leadership recognizes the current limited capacity of the RECOVER team, triggered in part by budget cuts and the loss of staff dedicated to the RECOVER program (Figure 6-4).

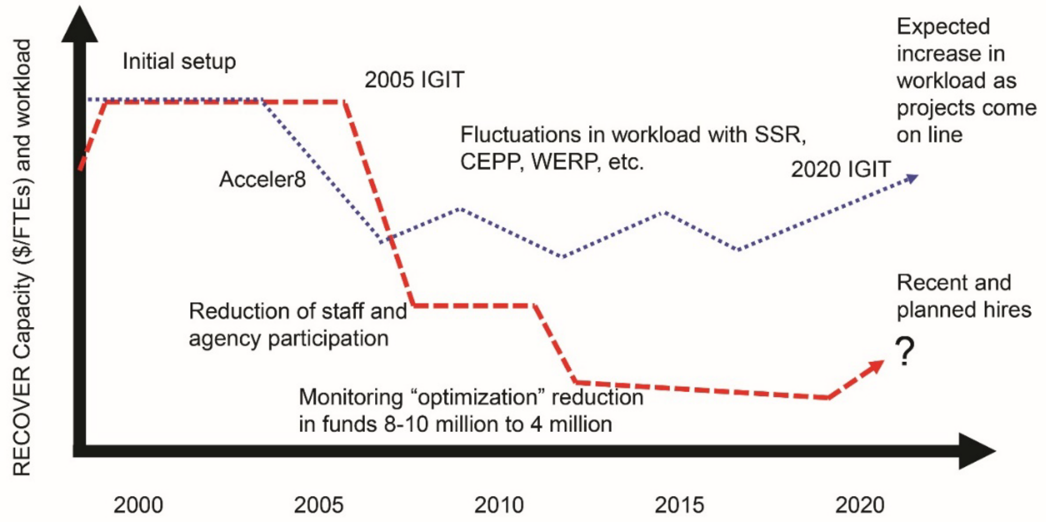

FIGURE 6-4 Conceptual RECOVER capacity (red dashed line) versus workload (blue dotted line) over time. SOURCE: Brandt et al., 2020.

In a complex system such as the Everglades, experienced restoration scientists and engineers bring valuable insights and skills. Understaffing already affects the capacity of RECOVER to support decision making (Figure 6-2), and retirements and attrition pose ongoing workforce challenges. Therefore, attention is needed toward identifying the skills, capacity, and vision needed in the CERP science workforce to support decision making moving forward and developing a strategy to maintain that capacity.

This organization infrastructure should also include staff support for improved communications and science translation capacity dedicated to helping communicate results clearly and effectively to decision makers and the outside community. Although many effective science communicators exist across the restoration effort, they typically have technical responsibilities that serve as primary missions, leaving little time to serve in a communications role.

As the tasks to support decision making shift toward assessment, operations, and adaptive management, the CERP should take advantage of existing experience and knowledge. Project-level adaptive management teams should utilize, where feasible, those who previously worked on the project development teams in addition to experts in analysis of monitoring data. Extension of the role of science experts from the project delivery team through the entire adaptive management chain could bolster learning and effectiveness. Currently within the USACE, projects are typically handed off to another agency or team for maintenance and operations after the project is built, with experience and learning developed in planning lost to the project implementation and operation.

Opportunities for using science effectively may also be hindered by organizational silos that separate CERP and non-CERP efforts. Critical learning opportunities exist within non-CERP efforts, such as the COP, which could inform CERP efforts in the central Everglades. However, the organizational infrastructure to support the COP remains undefined (see Chapter 4), which could undermine the potential outcomes of the CEPP. COP adaptive management could serve as a pilot of the organizational infrastructure needed to provide science support for adaptive management in CERP. CERP adaptive management decisions are best made in light of all opportunities for improvements, both within and outside of the CERP, if they are to achieve maximum effectiveness.

Finally, NASEM (2018) noted that the CERP could benefit from establishment of a formal central leadership with the responsibility to ensure adequate science for decision making. The report states: “Ensuring that investigative research and advances in tools and understanding are useful in a policy context requires a programmatic approach directly linked to the CERP effort, which may be best championed by an independent Everglades Lead Scientist empowered to coordinate and promote needed scientific advances.” Although there are many capable, experienced scientists who provide insights and leadership within the restoration, the report notes: “There is no central leader to support Everglades restoration fully focused on a vision for science, its continued development, and application across agencies.” This remains the case and is further compounded by forthcoming retirement of key science leaders.

In this chapter the committee has demonstrated how monitoring, modeling, and synthesis can collectively be used to support the CERP as it moves from project planning to operations and management of the partially restored system. Centralized, focused, trusted science leadership is needed to ensure the diverse science enterprise is effective and meeting the needs of decision makers. The long-anticipated change in the program status, from planning to operations and adaptive management, requires a new approach to science leadership. The identification and prioritization of science needs to support critical restoration decisions, ensuring the adequacy and relevance of the CERP science enterprise, and fostering communication and use of science in the restoration effort, requires that CERP identify and empower an individual or small dedicated team to lead the effort.

CONCLUSIONS AND RECOMMENDATIONS

The value of science—especially systems thinking and analysis—becomes even more important as the CERP pivots from a focus on planning and advancing individual projects to operations and management of the partially restored system. The transition from a focus almost exclusively on multiyear CERP planning efforts to providing support for ongoing adaptive management of numerous projects in parallel with ongoing planning of remaining projects will necessitate strengthened science support for decision making. CERP managers face an array of restoration decisions, including adaptive management either at the project or program level based on assessments of restoration performance, near-term operational adjustments, project sequencing, and investments in additional science. The best science should be actively integrated and synthesized to inform these decisions so that restoration benefits are maximized and opportunities for learning across both CERP and non-CERP projects are not lost. New and renewed strategies for monitoring, modeling, and synthesis can strengthen the science support for these decisions.

Some monitoring programs are falling short of their potential, and the value of data sets for decision making is being limited by lack of strategic monitoring design targeted at the information most needed by decision makers. Decisions are best supported when monitoring is strategically designed to address identified management decisions and key management questions, considering natural variability and sampling constraints. Assessing how current monitoring supports decision needs (e.g., adaptive management, operations, science needs) can focus resources and ensure appropriate data are being collected as the program transitions from a focus on project planning to also support operations and management of the partially restored system.

To better support decision making, the use of models should be expanded, including applications such as assessments of restoration progress and evaluations of future scenarios and vulnerabilities. The CERP has invested significantly to develop a robust set of modeling tools to guide the restoration process, but to date these models have been used mainly for project planning. Restoration decision making would benefit if the CERP could apply its modeling tools to also investigate questions related to restoration progress, adaptive management, and potential future vulnerabilities. Consideration should be given to how these modeling tools can further benefit CERP decision making, including using models to increase understanding of the Everglades ecosystem and its response to changing external conditions. The increased use of models will require additional human and technical capacity for model application and development.

A concerted effort to systematically compare and integrate models and observations is needed to improve decision making. Observations should be compared with model results to better understand model errors and their cause, and to improve model performance. The uncertainty in model predictions should be quantified and used to assess the implications of model uncertainty on decisions. Assimilation of observations and models can also be used to create a more comprehensive view of the current state of the system and can enhance the understanding of the effects of CERP amid natural variability.

A list of priority synthesis topics should be developed annually to advance synthesis in a coordinated way and increase system understanding for management needs. The list should consider the types of synthesis needed to support decision making, the data and information expected to be available, strategies for catalyzing the synthesis, and estimates of resource needs. The skills and expertise of existing synthesis centers, as well as Everglades science experts, should be leveraged to support CERP synthesis needs.

A renewed commitment to best practices in data management from all participants in CERP data collection would better support the value of data to support decision making and promote more comprehensive and nimble synthesis efforts. The use of data to support all types of decision making depends upon effective data management, quality assurance systems, and ease of access to a variety of users. All participants in CERP data collection activities should be required to abide by data quality assurance programs and contribute metadata and data to central and publicly accessible data management repositories in a reasonable time frame.

A nimble organizational infrastructure for science is needed to support restoration decision making in light of the CERP's transition toward operations and adaptive management of multiple completed projects. Information alone does not guarantee effective decision making. Utilizing and integrating scientific information into decision making at appropriate times and in relevant ways is crucial. This infrastructure should include several key elements:

- **Adequate staffing of appropriately trained scientists** that can respond to management needs by analyzing, synthesizing, and communicating evolving relevant scientific information.
- **Continuity of expertise to support adaptive management throughout the life cycle of restoration projects**, bringing technical expertise developed during planning to bear on data analysis and assessment of restoration progress toward goals.
- **Strong science leadership** to provide an efficient and direct linkage between decision makers who need timely summaries of ongoing work and emerging issues and scientists conducting research, modeling, and monitoring. Strong science leadership is also needed to guide future investments in monitoring, modeling, and synthesis toward critical decisions and to help catalyze these efforts.

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Appendix A

The National Academies of Sciences, Engineering, and Medicine Everglades Reports

This report represents the 16th report by the National Academies of Sciences, Engineering, and Medicine on Everglades restoration. This Appendix recaps key findings of the previous reports.

Progress Toward Restoring the Everglades: The Seventh Biennial Review, 2018 (2018)

In the 2018 report, the committee noted that a vision for planned Comprehensive Everglades Restoration Plan (CERP) storage, at least in the northern portion of the system, was now becoming clear, although the future storage to be provided by Lake Okeechobee remains unresolved. The committee concluded that documentation and analysis of incremental restoration benefits from project implementation to date have been inadequate, primarily because of limitations in project-level monitoring and assessment efforts. Improvements to the monitoring and assessment program, at both project and systemwide scales, were recommended to increase the usefulness of monitoring data for CERP decision makers. The report also recommended a mid-course assessment that analyzes projected CERP outcomes in the context of future stressors. Rather than continuing its primary focus on restoring predrainage conditions and basing decisions on the ability to achieve those conditions under contemporary climate (1965-2005), the report recommends that the CERP program emphasize restoration focused on the future of the South Florida ecosystem and build upon the accumulating knowledge base to support successful implementation of this program. This effort requires an integrated assessment of the performance planned CERP projects under future climate and sea level–rise scenarios and other stressors. With seven large projects authorized and awaiting appropriations for construction and three additional projects nearing the end of their planning processes, the report states that the time is right for a mid-course assessment. This information could then inform robust decisions about future planning, funding, sequencing, and adaptive management. Implementing a restoration program that is resilient to future conditions also requires a science program that can bring the latest information and tools into CERP planning and implementation.

Progress Toward Restoring the Everglades: The Sixth Biennial Review, 2016 (2016)

The 2016 biennial report finds that, 16 years into the Comprehensive Everglades Restoration Project (CERP), completed components of the project are beginning to show ecosystem benefits, but the committee had several concerns regarding progress. There has been insufficient attention to refining long-term systemwide goals and objectives and the need to adapt the CERP to radically changing system and planning constraints. It now is known that the natural system was historically much wetter than previously assumed, bringing into question some of the hydrologic goals embedded in the restoration plan. Sea-level rise will reduce the footprint of the system, temperature and evaporative water losses will increase, rainfall may become more variable, and more storage will likely be needed to accommodate future increases or decreases in the quantity and intensity of runoff.

Review of the Everglades Aquifer Storage and Recovery Regional Study (2015)

The Florida Everglades is a large and diverse aquatic ecosystem that has been greatly altered over the past century by an extensive water control infrastructure designed to increase agricultural and urban economic productivity. The Comprehensive Everglades Restoration Plan (CERP), launched in 2000, is a joint effort led by the state and federal government to reverse the decline of the ecosystem. Increasing water storage is a critical component of the restoration, and the CERP included projects that would drill more than 330 aquifer storage and recovery (ASR) wells to store up to 1.65 billion gallons per day in porous and permeable units in the aquifer system during wet periods for recovery during seasonal or longer-term dry periods.

To address uncertainties regarding regional effects of large-scale ASR implementation in the Everglades, the U.S. Army Corps of Engineers (USACE) and the South Florida Water Management District conducted an 11-year ASR Regional Study, with focus on the hydrogeology of the Floridan aquifer system, water quality changes during aquifer storage, possible ecological risks posed by recovered water, and the regional capacity for ASR implementation. At the request of the USACE, this report reviews the ASR Regional Study Technical Data Report and assesses progress in reducing uncertainties related to full-scale CERP ASR implementation. This report considers the validity of the data collection and interpretation methods; integration of studies; evaluation of scaling from pilot- to regional-scale application of ASR; and the adequacy and reliability of the study as a basis for future applications of ASR.

Progress Toward Restoring the Everglades: The Fifth Biennial Review, 2014 (2014)

This report is the fifth biennial evaluation of progress being made in the Comprehensive Everglades Restoration Plan (CERP). Despite exceptional project planning accomplishments, over the past 2 years progress toward restoring the Everglades has been slowed by frustrating financial and procedural constraints. The Central Everglades Planning Project is an impressive strategy to accelerate Everglades restoration and avert further degradation by increasing water flow to the ecosystem. However, timely authorization, funding, and creative policy and implementation strategies will be essential to realize important near-term restoration benefits. At the same time, climate change and the invasion of non-native plant and animal species further challenge the Everglades ecosystem. The impacts of changing climate—especially sea-level rise—add urgency to restoration efforts to make the Everglades more resilient to changing conditions.

Progress Toward Restoring the Everglades: The Fourth Biennial Review, 2012 (2012)

The 2012 biennial report finds that, 12 years into the Comprehensive Everglades Restoration Project, little progress has been made in restoring the core of the remaining Everglades ecosystem; instead, most project construction so far has occurred along its periphery. To reverse ongoing ecosystem declines, it will be necessary to expedite restoration projects that target the central Everglades, and to improve both the quality and quantity of the water in the ecosystem. The new Central Everglades Planning Project offers an innovative approach to this challenge, although additional analyses are needed at the interface of water quality and water quantity to maximize restoration benefits within existing legal constraints.

Progress Toward Restoring the Everglades: The Third Biennial Review, 2010 (2010)

The 2010 biennial report finds that while natural system restoration progress from the Comprehensive Everglades Restoration Plan remains slow, in the past 2 years, there have been noteworthy improvements in the pace of implementation and in the relationship between the federal and state partners. Continued public support and political commitment to long-term funding will be needed for the restoration plan to be completed. The science program continues to address important issues, but more transparent mechanisms for integrating science into decision making are needed. Despite such progress, several important challenges related to water quality and water quantity have become increasingly clear, highlighting the difficulty of achieving restoration goals simultaneously for all ecosystem components. Achieving these goals will be enormously costly and will take decades at least. Rigorous scientific analyses of potential conflicts among the hydrologic requirements of Everglades landscape features and species, and the trade-offs between water quality and quantity, considering timescales of reversibility, are needed to inform future prioritization and funding decisions. Understanding and communicating these trade-offs to stakeholders are critical.

Progress Toward Restoring the Everglades: The Second Biennial Review, 2008 (2008)

The report concludes that budgeting, planning, and procedural matters are hindering a federal and state effort to restore the Florida Everglades ecosystem, which is making only scant progress toward achieving its goals. Good science has been developed to support restoration efforts, but future progress is likely to be limited by the availability of funding and current authorization mechanisms. Despite the accomplishments that lay the foundation for CERP construction, no CERP projects have been completed to date. To begin reversing decades of decline, managers should address complex planning issues and move forward with projects that have the most potential to restore the natural ecosystem.

Progress Toward Restoring the Everglades: The First Biennial Review, 2006 (2007)

This report is the first in a congressionally mandated series of biennial evaluations of the progress being made by the Comprehensive Everglades Restoration Plan. The report finds that progress has been made in developing the scientific basis and management structures needed to support a massive effort to restore the Florida Everglades ecosystem. However, some important projects have been delayed due to several factors, including budgetary restrictions and a project planning process that can be stalled by unresolved scientific uncertainties. The report outlines an alternative approach that can help the initiative move forward even as it resolves remaining scientific uncertainties. The report calls for a boost in the rate of federal spending if the restoration of Everglades National Park and other projects are to be completed on schedule.

Re-Engineering Water Storage in the Everglades: Risks and Opportunities (2005)

Human settlements and flood control structures have significantly reduced the Everglades, which once encompassed more than 3 million acres of slow-moving water enriched by a diverse biota. The Comprehensive Everglades Restoration Plan (CERP) was formulated in 1999 with the goal of restoring the original hydrologic conditions of the remaining Everglades. A major feature of this plan is providing enough storage capacity to meet human and ecological needs. This report reviews and evaluates not only storage options included in the plan, but also other options not considered in the plan. Along with providing hydrologic and ecological analyses of the size, location, and functioning of water storage components, the report also discusses and makes recommendations on related critical factors, such as timing of land acquisition, intermediate states of restoration, and trade-offs among competing goals and ecosystem objectives.

The CERP imposes some constraints on sequencing of its components. The report concludes that two criteria are most important in deciding how to sequence components of such a restoration project: (1) protecting against additional habitat loss by acquiring or protecting critical lands in and around the Everglades and (2) providing ecological benefits as early as possible.

There is a considerable range in the degree to which various proposed storage components involve complex design and construction measures, rely on active controls and frequent equipment maintenance, and require fossil fuels or other energy sources for operation. The report recommends that, to the extent possible, the CERP should develop storage components that have fewer of those requirements and are thus less vulnerable to failure and more likely to be sustainable in the long term.

Furthermore, as new information becomes available and as the effectiveness and feasibility of various restoration components become clearer, some of the earlier adaptation and compromises might need to be revisited. The report recommends that methods be developed to allow for assessment of trade-offs over broad spatial and long temporal scales, especially for the entire ecosystem, and gives an example of what an overall performance indicator for the Everglades system might look like.

Adaptive Monitoring and Assessment for the Comprehensive Everglades Restoration Plan (2003)

A key premise of the CERP is that restoring the historical hydrologic regime in the remaining wetlands will reverse declines in many native species and biological communities. Given the uncertainties that will attend future responses of Everglades ecosystems to restored water regimes, a research, monitoring, and adaptive management program is planned. This report assessed the extent to which the restoration effort's "monitoring and assessment plan" included the following elements crucial to any adaptive management scheme: (1) clear restoration goals and targets, (2) a sound baseline description and conceptualization of the system, (3) an effective process for learning from management actions, and (4) feedback mechanisms for improving management based on the learning process.

The report concludes that monitoring needs must be prioritized, because many goals and targets that have been agreed to may not be achievable or internally consistent. Priorities could be established based on the degree of flexibility or reversibility of a component and its potential impact on future management decisions. Such a prioritization should be used for scheduling and sequencing of projects, for example. Monitoring that meets multiple objectives (e.g., adaptive management, regulatory compliance, and a "report card") should be given priority.

Ecosystem-level, systemwide indicators should be developed, such as land cover and land use measures, an index of biotic integrity, and diversity measures. Regionwide monitoring of human and environmental drivers of the ecosystem, especially population growth, land use change, water demand, and sea-level rise are recommended. Monitoring, modeling, and research should be well integrated, especially with respect to defining the restoration reference state and using "active" adaptive management.

Does Water Flow Influence Everglades Landscape Patterns? (2003)

A commonly stated goal of the Comprehensive Everglades Restoration Plan is to "get the water right." This has largely meant restoring the timing and duration of water levels and the water quality in the Everglades. Water flow (speed, discharge, direction) has been considered mainly in the coastal and estuarine system, but not elsewhere. Should the restoration plan be setting targets for flows in other parts of the Everglades as well?

There are legitimate reasons why flow velocities and discharges have thus far not received greater emphasis in the plan. These include a relative lack of field information and poor resolution of numerical models for flows. There are, however, compelling reasons to believe that flow has important influences in the central Everglades ecosystem. The most important reason is the existence of major, ecologically important landforms—parallel ridges, sloughs, and "tree islands"—that are aligned with present and inferred past flow directions. There are difficulties in interpreting this evidence, however, as it is essentially circumstantial and not quantitative.

Alternative mechanisms by which flow may influence this landscape can to some extent be evaluated from short-term research on underlying bedrock topography, detailed surface topographic mapping, and accumulation rates of suspended organic matter. Nonetheless, more extensive and long-term research will also be necessary, beginning with the development of alternative conceptual models of the formation and maintenance of the landscape to guide a research program. Research on maintenance rather than evolution of the landscape should have higher priority because of its direct impact on restoration. Monitoring should be designed for the full range of flow conditions, including extreme events.

Overall, flows approximating historical discharges, velocities, timing, and distribution should be considered in restoration design, but quantitative flow-related performance measures are not appropriate until there is a better scientific understanding of the underlying science. At present, neither a minimum nor a maximum flow to preserve the landscape can be established.

Florida Bay Research Programs and Their Relation to the Comprehensive Everglades Restoration Plan (2002)

This report of the Committee on Restoration of the Greater Everglades Ecosystem evaluated Florida Bay studies and restoration activities that potentially affect the success of the Comprehensive Everglades Restoration Plan (CERP). Florida Bay is a large, shallow marine system immediately south of the Everglades, bounded by the Florida Keys and the Gulf of Mexico. Some of the water draining from the Everglades flows directly into northeast Florida Bay. Other freshwater drainage reaches the bay indirectly from the northwest.

For several decades until the late 1980s, clear water and dense seagrass meadows characterized most of Florida Bay. However, beginning around 1987, the seagrass beds began dying in the western and central bay. It is often assumed that increased flows to restore freshwater Everglades habitats will also help restoration of Florida Bay. However, the CERP may actually result in higher salinities in central Florida Bay than exist presently, and thus exacerbate the ecological problems. Furthermore, some percentage of the proposed increase in fresh surface-water flow discharging northwest of the bay will eventually reach the central bay, where its dissolved organic nitrogen may lead to algal blooms. Complicating the analysis of such issues is the lack of an operational bay circulation model.

The report notes the importance of additional research in the following areas: estimates of groundwater discharge to the bay; full characterization and quantification of surface runoff in major basins; transport and total loads of nitrogen and phosphorus from freshwater sources, especially in their organic forms; effects on nutrient fluxes of decreasing freshwater flows into the northeastern bay, and of increasing flows northwest of the bay; and the development of an operational Florida Bay circulation model to support a bay water quality model and facilitate analysis of CERP effects on the bay.

Science and the Greater Everglades Ecosystem Restoration: An Assessment of the Critical Ecosystems Study Initiative (2003)

The Everglades represents a unique ecological treasure, and a diverse group of organizations is currently working to reverse the effects of nearly a century of wetland drainage and impoundment. The path to restoration will not be easy, but sound scientific information will increase the reliability of the restoration, help enable solutions for unanticipated problems, and potentially reduce long-term costs. The investment in scientific research relevant to restoration, however, decreased substantially within some agencies, including one major Department of the Interior (DOI) science program, the Critical Ecosystem Studies Initiative (CESI). In response to concerns regarding declining levels of funding for scientific research and the adequacy of science-based support for restoration decision making, the U.S. Congress instructed the DOI to commission the National Academy of Sciences to review the scientific component of the CESI and provide recommendations for program management, strategic planning, and information dissemination.

Although improvements should be made, this report notes that the CESI has contributed useful science in support of the DOI's resource stewardship interests and restoration responsibilities in South Florida. It recommends that the fundamental objectives of the CESI research program remain intact, with continued commitment to ecosystem research. Several improvements in CESI management are suggested, including broadening the distribution of requests for proposals and improving review standards for proposals and research products. The report asserts that funding for CESI science has been inconsistent and as of 2002 was less than that needed to support the DOI's interests in and responsibilities for restoration. The development of a mechanism for comprehensive restoration-wide science coordination and synthesis is recommended to enable improved integration of scientific findings into restoration planning.

Regional Issues in Aquifer Storage and Recovery for Everglades Restoration: A Review of the ASR Regional Study Project Management Plan of the Comprehensive Everglades Restoration Plan (2002)

The report reviews a comprehensive research plan on Everglades restoration drafted by federal and Florida officials that assesses a central feature of the restoration: a proposal to drill more than 300 wells funneling up to 1.7 billion gallons of water a day into underground aquifers, where it would be stored and then pumped back to the surface to replenish the Everglades during dry periods. The report says that the research plan goes a long way to providing information needed to settle remaining technical questions and clearly responds to suggestions offered by scientists in Florida and in a previous report by the National Research Council.

Aquifer Storage and Recovery in the Comprehensive Everglades Restoration Plan: A Critique of the Pilot Projects and Related Plans for ASR in the Lake Okeechobee and Western Hillsboro Areas (2001)

Aquifer storage and recovery (ASR) is a major component in the Comprehensive Everglades Restoration Plan, which was developed by the U.S. Army Corps of Engineers (USACE) and the South Florida Water Management District (SFWMD). The plan would use the upper Floridan aquifer to store large quantities of surface water and shallow groundwater during wet periods for recovery during droughts.

ASR may limit evaporation losses and permit recovery of large volumes of water during multiyear droughts. However, the proposed scale is unprecedented and little subsurface information has been compiled. Key unknowns include impacts on existing aquifer uses, suitability of source waters for recharge, and environmental and/or human health impacts due to water quality changes during subsurface storage.

To address these issues, the USACE and SFWMD proposed aquifer storage recharge pilot projects in two key areas. The charge to the Committee on Restoration of the Greater Everglades Ecosystem was to examine a draft of their plans from a perspective of adaptive management. The report concludes that regional hydrogeologic assessment should include development of a regional-scale groundwater flow model, extensive well drilling and water quality sampling, and a multiobjective approach to ASR facility siting. It also recommends that water quality studies include laboratory and field bioassays and ecotoxicological studies, studies to characterize organic carbon of the source water and anticipate its effects on subsurface biogeochemical processes, and laboratory studies. Finally, it recommends that pilot projects be part of adaptive assessment.

Appendix B

Biographical Sketches of Committee Members and Staff

Charles T. Driscoll, Jr., ***Chair***, is University Professor in the Department of Civil and Environmental Engineering at Syracuse University, where he also serves as the director of the Center for Environmental Systems Engineering. His teaching and research interests are in the areas of environmental chemistry, biogeochemistry, and environmental quality modeling. A principal research focus has been the response of forest, aquatic, and coastal ecosystems to disturbance, including air pollution, land use change, and elevated inputs of nutrients and mercury. Dr. Driscoll is currently an investigator of the National Science Foundation's Long Term Ecological Research Network's project at the Hubbard Brook Experimental Forest in New Hampshire. He is a member of the National Academy of Engineering and has served on several National Academy committees. He has also served on the Committee on Independent Scientific Review of Everglades Restoration Progress since 2006. He is a fellow of the American Academy for the Advancement of Science. Dr. Driscoll received his B.S. in civil engineering from the University of Maine and his M.S. and Ph.D. in environmental engineering from Cornell University.

William G. Boggess is professor and executive associate dean of the College of Agricultural Sciences at Oregon State University (OSU). Prior to joining OSU, Dr. Boggess spent 16 years on the faculty at the University of Florida in the Food and Resource Economics Department. His research interests include interactions between agriculture and the environment (e.g., water allocation, groundwater contamination, surface-water pollution, sustainable systems); economic dimensions and indicators of ecosystem health; and applications of real options to environmental and natural resources. Dr. Boggess previously served on the Oregon Governor's Council of Economic Advisors and the Board of Directors of the American Agricultural Economics Association, and he currently serves on the Board of the Oregon Environmental Council. He served on the State of Oregon Environment Report Science Panel and has been active in the design and assessment of the Oregon Conservation Reserve Enhancement Program. Dr. Boggess served as a member of the National Research Council Committee on the Use of Treated Municipal Wastewater Effluents and Sludge in the Production of Crops for Human Consumption, and on the Committee on Independent Scientific Review of Everglades Restoration Progress (since 2008), serving as chair of the fourth and seventh committees. He received his Ph.D. from Iowa State University.

Casey Brown is professor in the Department of Civil and Environmental Engineering at the University of Massachusetts at Amherst and adjunct associate research scientist at Columbia University. His primary research interest is the development of analytical methods for improving the use of scientific observations and data in decision making, with a focus on climate and water resources, and he has worked extensively on projects around the world in this regard. He chairs the Water and Society Technical Committee of the American Geophysical Union Hydrology Section and the Water Resources Planning under Climate Change Technical Committee of the American Society of Civil Engineers Environmental and Water Resources Institute Systems Committee. He earned his B.S. in civil engineering from the University of Notre Dame, his M.S. from the University of Massachusetts, Amherst, and his Ph.D. in environmental engineering science from Harvard University.

Robin K. Craig is the James I. Farr Presidential Endowed Professor of Law at the University of Utah College of Law. Her research focuses on "all things water," especially water, ocean, and coastal law; the impact of climate change on freshwater resources; and the intersection of water and energy law. She has published 11 books on environmental and water law and sustainability. Craig previously taught at the

Lewis & Clark School of Law; Western New England College School of Law in Springfield, Massachusetts; Indiana University-Indianapolis School of Law; and the Florida State University College of Law in Tallahassee, Florida. She served on prior National Academies' committees on the Clean Water Act and the Mississippi River and on the Edwards Aquifer Habitat Conservation Plan. She is active in the American Bar Association's Section on Environment, Energy, and Resources, where she just completed a 3-year term on the Executive Council and where she currently serves as Co-Chair of the Water Resource Committee. She received a B.A. from Pomona College, an M.A. from Johns Hopkins University, a Ph.D. in English literature from the University of California, Santa Barbara, and a J.D. from Lewis & Clark College.

Thomas Dunne (NAS) is research professor in the Donald Bren School of Environmental Science and Management at the University of California, Santa Barbara. He is a hydrologist and a geomorphologist, with research interests in field and theoretical studies of drainage basin and hill-slope evolution; sediment transport and floodplain sedimentation; debris flows; and sediment budgets of drainage basins. He served as a member of the Water Science and Technology Board Committee on Water Resources Research, the Committee on Opportunities in the Hydrologic Sciences, and the Committee on Sustainable Water and Environmental Management in the California Bay-Delta. He was elected to the National Academy of Sciences in 1988 and the American Academy of Arts and Sciences in 1992. He has acted as a scientific advisor to the United Nations, the governments of Brazil, Taiwan, Kenya, Spain, the Philippines, Washington, Oregon, and several U.S. federal and state agencies. He is a recipient of the American Geophysical Union Horton Medal and the Linsley Award of the American Institute of Hydrology. Dr. Dunne holds a B.A. from Cambridge University and a Ph.D. in geography from the Johns Hopkins University.

M. Siobhan Fennessy is the Philip and Sheila Jordan Professor of Environmental Science and Biology at Kenyon College, where she studies wetland ecosystems, particularly how wetland plant communities and biogeochemical cycles respond to human disturbances such as altered land use and factors associated with climate change. Her work has resulted in the development of biological assessment methods for wetlands that were recently employed in the National Wetland Condition Assessment effort led by the U.S. Environmental Protection Agency (EPA). She previously served on the faculty of the Geography Department of University College London and held a joint appointment at the Station Biologique du la Tour du Valat investigating human impacts to Mediterranean wetlands. She was a member of the EPA's Biological Assessment of Wetlands Workgroup, a national technical committee working to develop biological indicators of ecosystem condition. She recently co-authored a book on the ecology of wetland plants. Her current research focus is the alteration of ecosystem services that results from ecosystem degradation. She served as a member of the National Academies' Committee to Review the St. Johns River Water Supply Impact Study and since 2015 has served on the Committee on Independent Scientific Review of Everglades Restoration Progress. Dr. Fennessy received her B.S. in botany and Ph.D. in environmental science from The Ohio State University.

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Ehab A. Meselhe is professor in the Department of River-Coastal Science and Engineering at Tulane University. Dr. Meselhe has more than 25 years of experience researching coastal wetland hydrology, sediment transport, and computer modeling of coastal wetland, estuarine, and riverine systems. He worked as an educator, researcher, and practitioner with extensive experience working with academic institutions, government agencies, and the private sector. Dr. Meselhe served as Louisiana's technical lead for the Mississippi River Hydrodynamic and Delta Management Study and helped build the numerical models that provided a foundation for Louisiana's 2012 and 2017 Coastal Master Plans. Dr. Meselhe is heavily involved in the numerical modeling being used by Louisiana to help refine the design of sediment diversions at Mid-Barataria and Mid-Breton along the Mississippi River. Dr. Meselhe is a registered professional engineer in the states of Iowa and Louisiana. He also served as an Associate Editor of the *Journal of Hydrology* (Elsevier) and the *Journal of Hydraulic Research* (International Association of Hydraulic Research). He earned his B.S. from Zagazig University in Cairo, Egypt, and his M.S. and Ph.D. in civil and environmental engineering from the University of Iowa.

Denise J. Reed is a nationally and internationally recognized expert in coastal marsh sustainability and the role of human activities in modifying coastal systems with more than 30 years of experience studying coastal issues in the United States and abroad. Dr. Reed has served as a Distinguished Research Professor in the University of New Orleans' Department of Earth and Environmental Sciences, and spent 5 years as chief scientist at The Water Institute of the Gulf. She has served on numerous boards and panels addressing the effects of human alterations on coastal environments and the role of science in guiding restoration, including the National Research Council Committee on Sustainable Water and Environmental Management in the California Bay-Delta, and has been a member of the U.S. Army Corps of Engineers Environmental Advisory Board and the National Oceanic and Atmospheric Administration Science Advisory Board. Dr. Reed received her B.S. in geography from Sidney Sussex College, and her M.A. and Ph.D. from the University of Cambridge.

James Saiers is the Clifton R. Musser Professor of Hydrology at the Yale School of Forestry and Environmental Studies. Dr. Saiers studies how human activities and natural processes affect the quality of drinking-water resources and alter freshwater flows within aquifers, wetlands, and river basins. His recent research projects address water-quality impacts of fossil-fuel development, carbon and nutrient transport through watersheds, radionuclide migration in groundwater, and climate-change effects on water resources in Africa. Dr. Saiers has served on the Committee on Independent Scientific Review of Everglades Restoration Progress since 2012, and he chaired the Committee to Review the Florida Aquifer Storage and Recovery Regional Study Technical Data Report. Additionally, he served as a member of the Hydraulic Fracturing Research Advisory Panel of the Environmental Protection Agency Science Advisory Board. He earned his B.S. in geology from the Indiana University of Pennsylvania and his M.S. and Ph.D. in environmental sciences from the University of Virginia.

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Martha A. Sutula is a principal scientist and head of the Biogeochemistry Department of the Southern California Coastal Water Research Project, where she oversees projects related to the effects of climate change and anthropogenic pollution on acidification, hypoxia, harmful algal blooms, and eutrophication. Her research group combines the use of observations, experiments, and numerical models to understand drivers and ecological impacts of these phenomena in streams, lakes, estuaries, and coastal waters. Beyond her research activities, she focuses on linking science to management. Examples of this include her work as lead scientist to the California State Water Resources Control Board, providing technical support to develop eutrophication water quality objectives for California's waters. She received her B.S.

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Jeffrey R. Walters is the Harold Bailey Professor of Biology at Virginia Tech, a position he has held since 1994. His professional experience includes assistant, associate, and full professorships at North Carolina State University from 1980 until 1994. Dr. Walters has done extensive research and published many articles on the red-cockaded woodpeckers in North Carolina and Florida, and he chaired an American Ornithologists' Union Conservation Committee Review that looked at the biology, status, and management of the Cape Sable seaside sparrow, a bird endemic to the Everglades. His research interests are in the behavioral ecology, population biology, and conservation of birds, and his recent work has focused on cooperative breeding, dispersal behavior, and endangered species issues. Dr. Walters served on two panels of the Sustainable Ecosystems Institute that addressed issues with endangered birds in the Everglades restoration in addition to previously serving as a member of the National Academies' Committee on Restoration of the Greater Everglades Ecosystem and four previous terms of the Committee on Independent Scientific Review of Everglades Restoration Progress. He holds a B.A. from West Virginia University and a Ph.D. from the University of Chicago.

Denice H. Wardrop is research professor and professor of geography and ecology at The Pennsylvania State University. She also serves as associate director of Riparia. Her research focuses on theoretical ecology, anthropogenic disturbance and impacts on aquatic ecosystem function, ecological indicators, and ecosystem condition monitoring and assessment. Dr. Wardrop is the Pennsylvania Governor's Appointee to the Chesapeake Bay Program's Science and Technical Advisory Committee and previously served as its chair. She also directs the Mid-Atlantic Wetlands Workgroup. She has a B.S. in systems engineering from the University of Virginia, an M.S. in environmental sciences from the University of Virginia, and a Ph.D. in ecology from The Pennsylvania State University.

STAFF

Stephanie E. Johnson, study director, is a senior program officer with the Water Science and Technology Board. Since joining the National Research Council in 2002, she has worked on a wide range of water-related studies, on topics such as desalination, wastewater reuse, contaminant source remediation, coal and uranium mining, coastal risk reduction, and ecosystem restoration. She has served as study director for 20 committees, including the Panel to Review the Critical Ecosystem Studies Initiative and all seven Committees on Independent Scientific Review of Everglades Restoration Progress. Dr. Johnson received her B.A. from Vanderbilt University in chemistry and geology and her M.S. and Ph.D. in environmental sciences from the University of Virginia.