SCIENTIFIC AND TECHNICAL KNOWLEDGE GAINED IN EVERGLADES RESTORATION (1999-2009)

REstoration COordination and VERification (RECOVER)

June 2010

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INTRODUCTION

The Comprehensive Everglades Restoration Plan (CERP or Plan) provides a framework and guide to restore, protect and preserve the water resources of central and southern Florida, including the Everglades. It covers 16 counties over an 18,000-square-mile area and centers on the Central and Southern Florida Project Comprehensive Review Study, also known as the Restudy (1999). The Plan was approved in the Water Resources Development Act (WRDA) of 2000 and includes more than 60 elements that will take more than 30 years to construct. Much has been learned about the Everglades and south Florida ecosystem since the Restudy. Restoration Coordination and Verification (RECOVER), the scientific arm of CERP, has developed the Scientific Knowledge Gained (SKG) Document to summarize what has been learned since the Restudy including information from monitoring and research, engineering, and modeling. The intent of the SKG Document is to provide a factual, accessible scientific reference for managers, scientists, and all interested parties. The summaries are short and relatively easy to read, making them useful to managers and interested parties who may not have the time, resources, or the specialized knowledge needed to sort through primary scientific literature. The SKG Document both draws from, and is complementary to, other efforts including the RECOVER Monitoring and Assessment Plan (MAP), peer-reviewed scientific journals, publically available agency research, computer modeling, and results presented at scientific conferences. The SKG Document is part of a larger effort called the 2010 Shared Definition of Everglades Restoration (Shared Definition) – the goal of this effort is to better define the functional attributes of a restored Everglades in order to provide enhanced information for planning, implementation and operation of restoration projects. More information can be found in the Shared Definition Letter of Intent and FAQs.

The SKG Document is organized around the five critical components of Everglades restoration identified by the Committee on Independent Scientific Review of Everglades Restoration Progress (CISRERP) in their reports (NRC, 2006; NRC, 2008). These critical components needed for restoration are:

1. **Water storage capacity:** 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. **Water delivery:** 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;
3. **Seepage:** 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. **Water quality:** 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. **Habitats:** 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.

In addition to these five critical components, the SKG Document also has sections devoted to the potential impacts of **climate change** and advances and updates in **predictive modeling**.

The SKG Document contains summaries of approximately 50 topics, each limited in length to two pages. Readers can read the entire document or just topics of interest. The topics were chosen by a RECOVER team, and the team acknowledges that important topics may be missing; topics can be added after consideration by the team and if an appropriate author is available. The topics were chosen according to the following criteria: (1) relevance to Everglades restoration, particularly topics that were identified as areas of scientific uncertainty in the Restudy; (2) relevance to the five critical components of Everglades restoration described above; and (3) availability of new information since the Restudy. Authors were chosen for their areas of expertise, their availability, and according to the requirements of the Federal Advisory Committee Act (FACA). Authors consisted of RECOVER and agency staff and their specialized science and technical support contractors. In addition, draft summaries were internally reviewed by subject matter experts who provided substantial input throughout the iterative review and editing process. Broader input was received via online reviews and public workshops during the document's development.

Readers familiar with other current science synthesis efforts Everglades restoration may ask how the SKG document is different than and compliments the others. The SKG provides a "middle level" of detail; a reader seeking more detail on a particular topic can look into the bibliography citations and comprehensive reports such as the System Status Reports (SSR). A reader seeking less detailed plain English overviews can refer to the Science Coordination Group's New Science brochure and System-wide Indicators (stoplight) Reports, and the summary chapters of the SSRs.

Readers may find it helpful to know the writing guidelines that the authors followed. Authors were asked to provide concise, balanced synthesis of new scientific knowledge gained since the Restudy on a designated topic. They were limited to approximately two pages of text, plus figures and references. They were asked NOT to provide recommendations, prescriptions, opinions, inferences, and/or proclamations. They were required to substantiate their summaries with thorough bibliographic references, as would be required for a peer-reviewed, scientific article for publication. Acceptable sources of information included peer-reviewed scientific literature, publically available agency reports and grey literature, conference proceedings, and other sources that are standard in peer-reviewed science publications. They were also asked only to cite materials that could be accessed within reason by a public reader. Please see the SKG Document instructions to authors for more information.

LEGAL JUSTIFICATION FOR SCIENTIFIC KNOWLEDGE GAINED DOCUMENT AND RESTORATION COORDINATION AND VERIFICATION (RECOVER) INVOLVEMENT

The Final Integrated Feasibility Report and Programmatic Environmental Impact Statement produced by the Restudy outlined the broad, system-wide goals and objectives that are the basis of the Comprehensive Everglades Restoration Plan (CERP): to enhance ecologic values, and to enhance economic values and social well-being[1]. It provided descriptions of components that must be restored to achieve these goals[2] and discussed the reasons why complete ecological restoration in south Florida is impossible[3]. It stated "For this restoration project to be successful, it must recover important ecological components and patterns which are thought to have characterized the pre-drainage system, and it must be able to sustain these recovered ecological attributes over long time scales"[4]. The Restudy proceeded to state that, at the time of its development, "*…the point at which restoration is achieved, and the precise characteristics of that 'restored' system, represent questions that are not completely answerable at present*"[5] (emphasis added).

Part of the reason why success was not defined specifically by the Restudyis that at that time few of the quantitative, ecological characteristics of the pre-drainage wetlands of south Florida were known[6]. The Restudy predicted that "Consensus over the question of what a restored south Florida ecosystem should be, especially over the specific spatial, temporal, and numerical targets for restoration, should emerge over time, as system responses from initial projects begin to provide focus for the debate, and new modeling results and empirical data become available"[7]. Additionally, the Restudy envisioned that over the course of the restoration process scientific understanding of the pre-drainage system would increase, as knowledge is derived from models and studies of the current system[8].

This new information would be gained through the adaptive assessment (*i.e.*, adaptive management) process, which utilizes monitoring to understand the current system and measure responses to project actions, as well as conceptual ecological models to predict responses to projects and create measurable indicators of project success. The Natural Research Council, as

[1] USACE and SFWMD. 1999. Central and South Florida Comprehensive Review Study Final Integrated Feasibility Report and Programmatic Environmental Impact Statement (i.e., "Yellow Book"). Page 5-21, Table 5-1 outlines the Goals and Objectives for the C&SF Restudy.
[2] Yellow Book pages 5-21 through 5-26 further describe the components that must be restored to achieve these goals.
[3] Yellow Book page 5-36 states "For these reasons, and because *complete restoration is not possible*, the natural resource specialists in south Florida lack a strong consensus as to the restoration 'endpoint'; i.e., there is a range of legitimate answers to the question, 'what constitutes restoration?"
[4] Yellow Book page 5-36.
[5] Yellow Book page 5-37.
[6] Yellow Book page 5-36.
[7] Yellow Book page 5-38.
[8] Yellow Book page 5-36 states "The Restudy Team has attempted to understand the pre-drainage system, using such tools as the Natural System Model, and by creating conceptual ecological models of the major landscape features of Florida. These conceptual models have been developed from a series of hypotheses about the ecological relationships and biological components of the pre-drainage system, which have been derived from studies of the current system."

cited by the Restudy, described adaptive assessment by saying, "Rather than developing a fixed goal and an inflexible plan to achieve the goal, adaptive assessment recognizes that there always will be gaps in knowledge regarding the relationships within and among natural and social systems, and that these information gaps require that plans be modified as technical information improves and social preferences change. For adaptive assessment to succeed, the new knowledge gained (through monitoring) should be translated into restoration policy and program redesign over time and be shared across restoration programs at all levels of government"[9].

The Programmatic Regulations require that CERP be implemented such that it is continuously improved based on new scientific/technical information and utilizes the principles of adaptive management[10]. Restoration Coordination and Verification (RECOVER) play a prominent role in meeting this requirement, as RECOVER activities are based on an adaptive management approach. RECOVER was established to "conduct assessment, evaluation, and planning and integration activities using the best available science that support implementation of the Plan with the overall goal of ensuring that the goals and purposes of the Plan are achieved"[11]. The Programmatic Regulations further elaborate on the activities of RECOVER, each of which contributes in some way to refining the overall definition of CERP success. RECOVER is charged with developing system-wide performance measures, which assess progress towards achieving the goals and purposes of the Plan[12]. RECOVER also develops recommendations for interim goals and interim targets, which provide a means by which the restoration success of the Plan may be evaluated at specific points in the implementation process[13]. In addition, RECOVER "may propose revisions to the initial set of interim goals as new information is gained through adaptive management[14]." These activities help to refine the broad goals and objectives described in the Restudy by providing a quantitative basis for evaluating the restoration success of the Plan. RECOVER develops predictive models and tools, which help integrate new scientific information into CERP planning[15]. Finally, RECOVER is responsible for developing a monitoring program and conducting monitoring and assessment activities, which provide new scientific information in order to assess progress towards CERP goals and objectives as projects are implemented[16]. Information gained from RECOVER activities is used to inform management actions to continuously improve the Plan and ensure that goals and objectives are achieved.

As stated in the introduction, the Scientific Knowledge gained (SKG) document is intended to summarize new scientific and technical knowledge gained since the Restudy. Much of that new knowledge was obtained through RECOVER monitoring activities, then assessed and summarized in a technical report (i.e., the System Status Report), as required by the

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[9] Yellow Book, page 5-32; National Resource Council. 1992.. Committee on Restoration of Aquatic Ecosystems – Science, Technology, and Public Policy. Washington, D.C.: National Academy Press.
[10] Department of Defense. 2003. Programmatic Regulations for the Comprehensive Everglades Restoration Plan; Final Rule. Department of Defense, Federal Register, 33 CFR Part 385, November 12, 2003. §385.31(a)
[11] Programmatic Regulations, §385.20(a)
[12] Programmatic Regulations, §385.20(e)(1)(i)
[13] Programmatic Regulations, §385.20(e)(1)(i)(1)(iv-vii)
[14] Programmatic Regulations, §385.38(c)(1)
[15] Programmatic Regulations, §385.20(e)(2)(iii)
[16] Programmatic Regulations, §385.20(e)(1)(ii-iii)

Programmatic Regulations[17]. RECOVER work products are not self-executing, but are used to inform management actions and decision making[18], and the SKG document is no exception. RECOVER activities and work products will be essential in refining the definition of CERP success, and thus RECOVER involvement in the process is reasonable and expected.

[17] Programmatic Regulations, §385.31(b)(4)
[18] Programmatic Regulations, §385.20(b)

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PARTICIPATING AGENCIES AND TRIBES

The following is a list of the agencies and tribal affiliations of technical staff involved in authoring and reviewing summaries within the current draft document, along with their acronyms. The content/opinions expressed herein do not necessarily represent the opinions of these entities.

DOI	Department of the Interior
ENP	Everglades National Park
FDACS	Florida Department of Agriculture and Consumer Services
FDEP	Florida Department of Environmental Protection
FWC	Florida Fish and Wildlife Conservation Commission
NOAA	National Oceanic and Atmospheric Administration
	Miccosukee Tribe of Indians of Florida
NPS	National Park Service
	Seminole Tribe of Florida
SFWMD	South Florida Water Management District
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USEPA	Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service

In addition, many technical staff under contract to various agencies listed above were involved in authoring and reviewing these summaries.

1 EVERGLADES HYDROLOGY: KNOWLEDGE GAINED

This section of the Scientific Knowledge Gained (SKG) document addresses the following two components identified by the Committee for Independent Scientific Review of Everglades Restoration Progress (CISRERP) as critical for Everglades restoration (NRC, 2006; NRC, 2008):

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.

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.

1.1 Pre-drainage Hydrology of the Everglades

Authors: Christopher McVoy and Colin Saunders (SFWMD)

The decade since the Restudy has seen significant advances in ~~our~~ the understanding of the predrainage Everglades, more specifically, the Everglades of the 1800s (pre-1882). Most key aspects are now known, providing a reference condition both for restoration planning and for interpreting studies of the current, highly altered system. Understanding of the predrainage Everglades also forms an important basis for predicting system trajectories that can be expected under proposed restoration scenarios. The recent understanding has emerged from two independent approaches: paleoecological studies and an extensive analysis of historical data. The historical analysis, documented in detail in a book to be published in 2011 by the University Press of Florida (McVoy et al., in press), synthesizes soil data, vegetation data, land survey records and numerous other firsthand, predrainage observations. The paleoecological studies of Everglades soil cores (e.g., Willard et al., 2001, 2007; Winkler et al., 2001; Saunders et al., 2006; Bernhardt and Willard, 2009) shed light on much longer time periods. For the 1800s and early 1900s, when the historical analysis and paleoecological studies overlap in time, the two approaches corroborate each other. Both show that, with the possible exception of the southernmost portions of the current Water Conservation Areas 1, 2A, and 3A, water depths and hydroperiods were greater during the predrainage period. Further corroboration comes from inverse modeling of Florida Bay paleo-salinity, which also indicates greater predrainage water depths and flow rates under predrainage conditions (2.5 to 4 times faster than those presently found in Shark River Slough~~;~~ [Marshall et al., 2008]). Even when accounting for natural climate variations (discussed at the end of this section), paleoecological studies suggest that a number of predrainage aspects found in the historical synthesis (McVoy et al., in press) for the 1800s would also have been present during several preceding centuries as well (Bernhardt and Willard, 2009).

While the general outlines of predrainage Everglades hydrology were known during the Restudy, a number of important aspects were not or were in fact inaccurately characterized at that time. The earliest comprehensive maps of the Everglades were a map of soils (Jones et al., 1948) and a map of vegetation (Davis, 1943). Both maps were based on extensive fieldwork and successfully captured the conditions present in the 1940s. Unfortunately, the high quality of these maps, combined with the absence of equally detailed earlier ones, led naturally to the assumption that these maps were also good representations of predrainage conditions. This created two significant problems for restoration planning: first, a number of post-drainage features were incorrectly assumed to have been present in the predrainage system; and second, it was incorrectly assumed that the 1920-1940 time period formed an appropriate predrainage base against which to compare current conditions. Examples of the first problem include the following features, seen in the 1940s, but not actually present under predrainage conditions: (1) an elevated rim along the south shore of Lake Okeechobee; (2) "peripheral short hydroperiod wetlands" ("wet prairies") along the eastern and western margins of the Everglades, north of the latitude of Tamiami Trail; and (3) a large central band of sawgrass marsh separating the Ridge and Slough landscape into disjoint eastern and western areas. In actuality, no rim was originally present, so Lake Okeechobee outflows into the Everglades occurred in most years and throughout much of the year (McVoy et al., in press, chapter 5; where not otherwise noted, results are from this source). North of Tamiami Trail, the Ridge and Slough landscape originally extended directly up to the bordering forested uplands, so peripheral short hydroperiod wet prairies are not in fact a "lost" component of the landscape (McVoy et al., in press, chapters 2-4). And finally, the Ridge and Slough landscape originally extended across the full width of the Everglades, without a central band of sawgrass (McVoy et al., in press, chapters 3-4).

Examples of the second problem within the Ridge and Slough landscape include the use of 1940s data as a measure of the predrainage area of tree islands and the use of 1920s and 1930s data as a measure of predrainage wading bird spatial distributions. Uncontrolled drainage, combined with the absence of impoundments during the 1920s through 1940s, meant that Everglades water depths were greatly reduced during this period (McVoy et al., in press, chapter 2). Lowered water depths created drier conditions on the elevated areas (sawgrass ridges and tree islands), in turn anthropogenically increasing the area colonized by woody (tree island) species (McVoy et al., in press, chapter 3; Simpson, 1920; Robertson, 1953). At the same time, lowered water depths in sloughs very likely increased prey availability for wading birds because predrainage depths were usually too deep for most wading bird feeding (McVoy et al., in press, chapter 11). Both problems illustrate the challenges of planning restoration without an accurate picture of the original condition.

The Ridge and Slough landscape is now better understood than at the time of the Restudy, including its predrainage condition, the driving forces that previously sustained it, and the postdrainage changes to those driving forces that have caused substantial landscape alterations. This landscape, comprising most of the presently remaining Everglades, was geomorphologically a "patterned peatland." Differences in peat elevations (microtopography) and hence in hydrology, created a characteristic spatial distribution of slough, ridge and tree island vegetation. The linear, directional pattern of peat and vegetation in turn sustained a unique system of faunal habitats, including an enormous extent of ridge-slough interface and a seasonally changing aquatic/terrestrial relation between ridges and sloughs. While full understanding of the mechanisms sustained this landscape is the subject of active research, it is already clear that water depth regimes, water flow, and organic floc transport all are important (e.g., Science Coordination Team 2003; Harvey et al., 2009; Larson et al., 2009a, 2009b, 2009c; Noe et al., 2010). Water flows, depths, floc transport, and ultimately landscape pattern are all closely intertwining with slough vegetation types, suggesting a strong landscape sensitivity to predrainage hydrologic conditions. Sheet flow-- the uniform and unimpeded distribution of flow velocities across all sloughs--appears to be key to preserving the habitats created by Ridge and Slough patterning. Postdrainage losses of pattern in areas of altered hydrology confirm this linkage.

The spatial distribution of water depths within the predrainage Everglades, especially in the downstream direction, is a key aspect of understanding the differences between the present managed system and the predrainage one. The predrainage water surface paralleled the ground surface. Thus at any given time, water depths in sloughs throughout the Ridge and Slough landscape--including in Shark River Slough--were very similar (***Figure 1-1***). This was reflected in the presence of water lily (*Nymphaea odorata*) peats, and of water lilies themselves, in sloughs throughout the landscape. In contrast, the current impoundments (Water Conservation Areas) tend, at least part of the year, to level the water surface. The resultant "water wedges" (***Figure 1-2***) have far-reaching ecological implications. Peat oxidation (and elevation loss) on upstream tree islands can occur simultaneously with extended inundation periods on downstream tree islands. Moving fronts of optimal water~~r~~ depths for wading bird feedings are an anthropogenic creation.

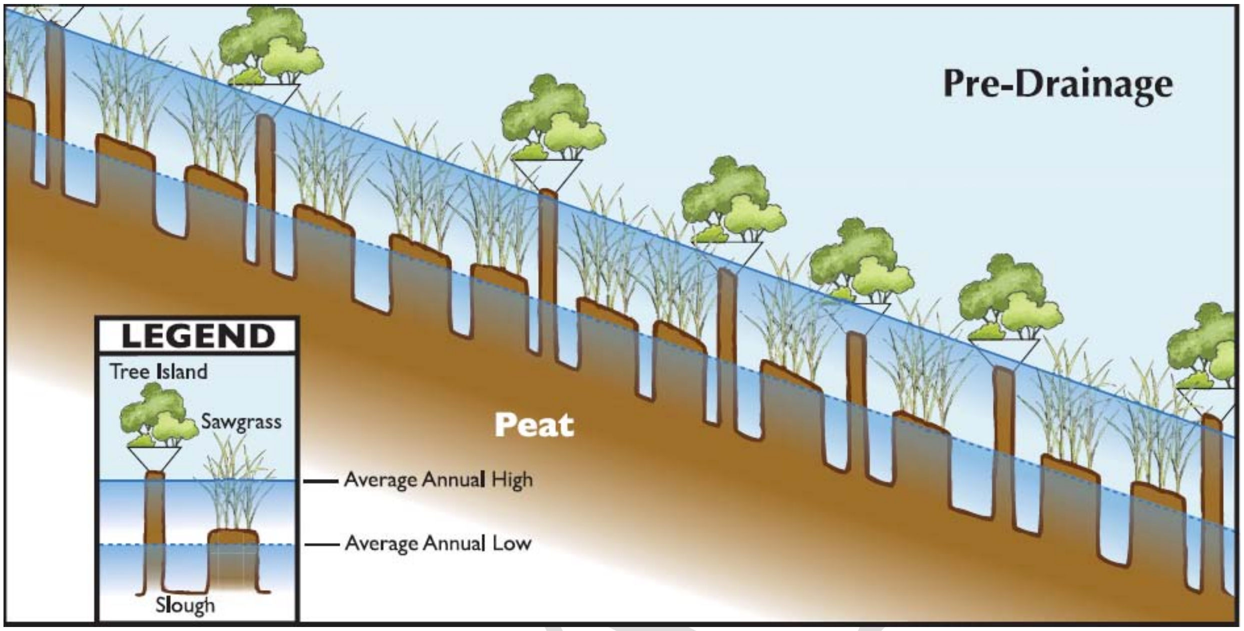

FIGURE 1-1: PRE-DRAINAGE

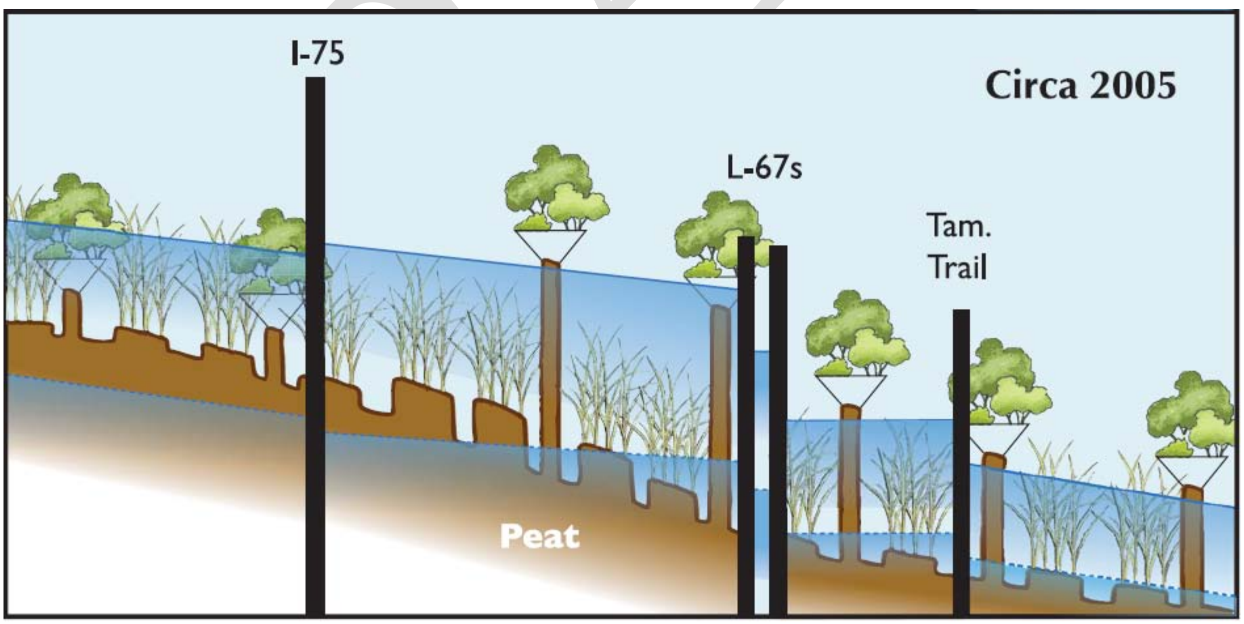

FIGURE 1-2: CIRCA 2005

Predrainage sloughs generally retained water throughout the year (***Table 1-1***), with complete loss of surface water reported only infrequently, roughly every 20 or 30 years. Water in sloughs was deep enough to favor water lilies and open water over emergent stands of "wet prairie" species such as Eleocharis or Rhynchospora. These more open predrainage sloughs permitted canoe mileages of 10 or even 15 miles a day (e.g., Smith 1848; see McVoy et al., in press, chapters 1, 8, and 11) and was also critical to unrestricted transport of organic floc (Larson et al. 2009b). Predrainage tree island heights varied considerably, between ~~about~~approximately two ~~and~~to four feet above surrounding sloughs, with some dry enough to allow seasonal cultivation and many low enough to provide only "boggy" camp sites. Predrainage flow directions are well-known, and indicate a very slight and gradual topographic rise toward the center of the Everglades, leading to divergent outflow areas. To the southeast, Everglades waters discharged through a series of continuously flowing rivers that pierced the Atlantic Coastal Ridge between Ft. Lauderdale and Miami. To the southwest, Everglades waters passed through present day Northeast Shark River Slough and Shark River Slough. These and most other features of predrainage Everglades hydrology have been captured in a surface water simulation model, the Natural System Regional Simulation Model (NSRSM), developed ~~at~~by the South Florida Water Management District (SFWMD).

The portion of the Everglades south of Tamiami Trail was originally much wetter than at present, with Shark River Slough being almost indistinguishable from the rest of the Ridge and Slough landscape further upstream. The present day marl prairies flanking Shark River Slough (Ochopee and Rockland landscapes) were also much wetter, with both sawgrass and slough-like areas present. Recent paleoecological studies (Willard et al., 2008; Saunders et al. 2008) and historical studies (McVoy et al., in press, chapters 9 and 11; Scheidt et al. 2000) both suggest the presence of a degree of peat that has been lost under drainage. The Ochopee and Rockland landscapes probably differed from the Ridge and Slough landscape in having been less directional in pattern and likely somewhat drier.

Paleoecological studies confirm that the predrainage (1800s) Everglades was wetter than most remaining modern locations, but they also add a longer term perspective. Emerging research suggests the presence of climatic "teleconnections" between oceanic atmospheric processes and the climate of South Florida (Cronin et al., 2002; Willard et al., 2006; Bernhardt and Willard, 2009). Teleconnections to processes such as the Atlantic Multidecadal Oscillation (AMO), the Intertropical Convergence Zone (ITCZ), the El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Pacific North American (PNA) index, and Central North Pacific (CNP) index introduce, at the scale of centuries, variability into the ~~S~~south Florida climate and hence into Everglades hydrology. Studies that further quantify predrainage relationships between climatic and hydrologic variability will likely prove helpful in improving future water management, given the likelihood of anthropogenic climate changes.

TABLE 1-1: PREDRAINAGE WATER DEPTHS AND HYDROPERIODS FOR EVERGLADES LANDSCAPES

Everglades Landscape	Average Annual Low (feet)	Average Annual High (feet)	Average Hydroperiod (months)
Custard Apple Swamp	0	2	11-12
Sawgrass Plains	-0.5*	1.5	9-10
Ridge and Slough (sloughs)	1	3	12
Ridge and Slough (ridges)	-0.5	1.5	9-10
Rockland & Ochopee Marl Marshes**	-0.5	2	8-9
Perrine Marl Marsh**	-1	1.5	8-9

* Negative values indicate distance below ground surface.
**Water depths across these landscapes were not uniform; values shown are for mid-elevation locations, i.e., about half way from Shark Slough to upper edge of landscape.

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1.2 Pre-drainage Flows and Salinities in Coastal Systems: Effects of Flow and Rainfall on Salinity in Florida Bay

Author: Don Deis (USACE Contractor)
Contributing reviewer: Sue Kemp (USACE)

At present, salinity in Florida Bay is more strongly correlated to rainfall than any other single factor (Hunt and Nuttle, 2007). The study of salinity patterns in Florida Bay begins with a "usable" database from approximately 1955 (Robblee at al., 2001).

Robblee et al. (2001) demonstrated that the salinity patterns within regions of Florida Bay (***Figure 1-3***) generally follow the pattern of rainfall within the bay (***Figure 1-4***). Florida Bay demonstrated a pattern of a negative/hypersaline estuary in 1957, 1975, and 1990 after two or more dry years; a positive estuary in 1995 after a series of wet years; and a marine lagoon in 1982, 1985, and 1993 in average years.

Figure 1-5 demonstrates that, in the period between 1955 and 1999, hypersalinity (greater than 40 practical salinity units [psu]) occurred most frequently in the central area (centered by Whipray Basin), but can also occur in the eastern area (centered on the Nest Keys), the western area (centered on Johnson Key Basin), and even, at times, in the upper estuaries (Long Sound, Joe Bay, and Little Madeira Bay).

As indicated in the *Technical Documentation to the Development of Minimum Flows and Levels (MFL) for Florida Bay* (SFWMD, 2006), a notable factor affecting Florida Bay was the completion of the C-111 Canal and the deliveries of water through the headwaters of Taylor Slough and the C-111 Canal system. Flows through Taylor Slough Bridge (TSB) and the C-111 Canal were low in the period of 1970 to 1981 relative to the flows after 1981. Changes in water management activities resulted in up to a four-fold increase in water delivery into this area. TSB was not affected by this increase until approximately 1993. Prior to 1993 annual discharges through TSB were less than 24,000 acre-feet (20 X 10^6 m^3/year); after 1993, annual discharges were up to 100,000 acre-feet (80 X 10^6 m^3 /year), averaging approximately 50,000 acre-feet (40 X 10^6 m^3/year) from 1991 through 2009 (***Figure 1-6).*** The affect of this delivery pattern is illustrated in the MFL technical documentation (SFWMD, 2006) by water year 1975 which was normal in terms of precipitation but had total annual inflow comparable to the 1989-1990 drought period which culminated in the collapse in seagrasses in Florida Bay.

Robblee (2001) provides a comparison of salinity within ten psu bins in the areas of Florida Bay shown in (***Figure 1-7***). The occurrence of hypersalinity events has been reduced in all of the areas of Florida Bay, with the central and western areas showing a few occurrences after 1993. This clearly shows the potential for stabilization of salinity in Florida Bay through increased freshwater deliveries through Taylor Slough.

Recent analysis of salinity data from 2004 to 2009 from all regions of Florida Bay in the 2009 System Status Report (SSR) finds salinity greater than 40 psu within many of the areas of the bay in the dry season. Annual flow data from TSB (***Figure 1-8***) shows that flows during the 2004 – 2009 analysis period was well below the 25-year average (Woods and Zucker, 2009). The low flows experienced in 2006 and 2007 are at or near the minimum flow recommended by the technical documentation for MFLs in Florida Bay (SFWMD, 2006). Woods and Zucker (2009) report that salinity conditions within the Trout River were at or above oceanic salinity 14.5 percent of the time in 2008. This confirms the conclusions that consecutive low flow years result in high salinity conditions in Florida Bay.

Summary

Salinity data collected since 1955 clearly shows that Florida Bay fluctuates with precipitation (and evapotranspiration) and that stabilization of salinity is maintained and hypersalinity events may be prevented through freshwater inflow from the Everglades system. Freshwater inflow from the Everglades has been modified through management, over the time of salinity data collection, and problems in the stabilization of salinity have been demonstrated when sufficient freshwater flow is not available.

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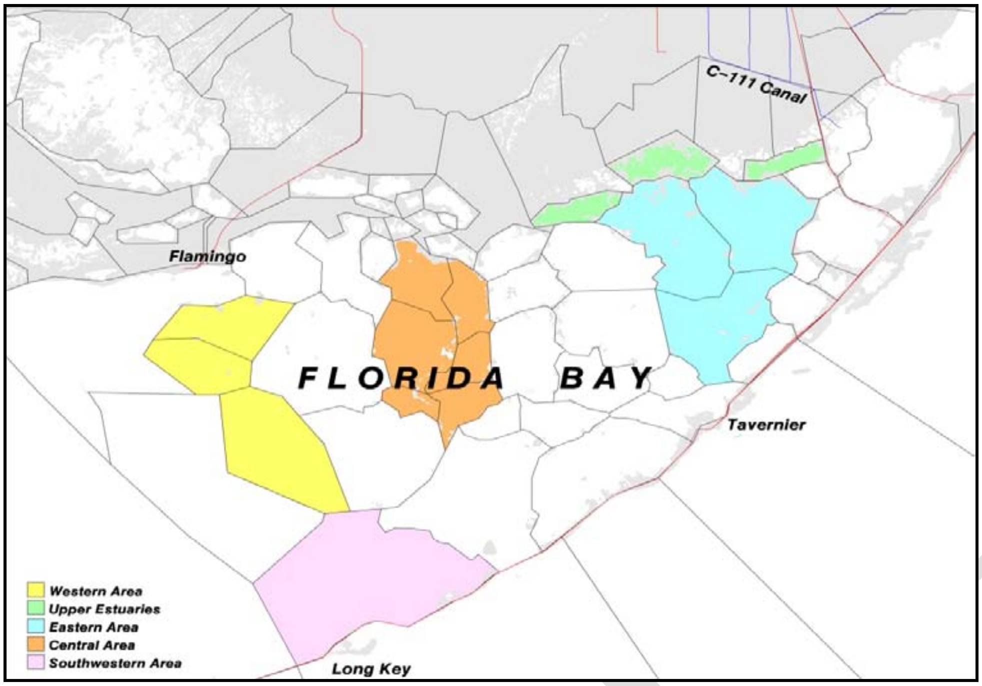
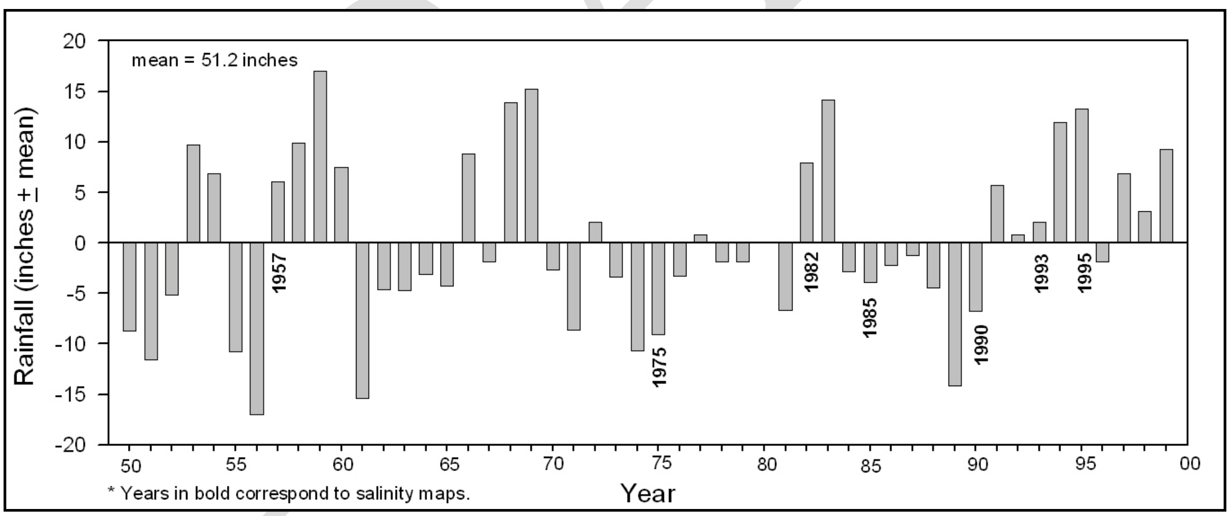
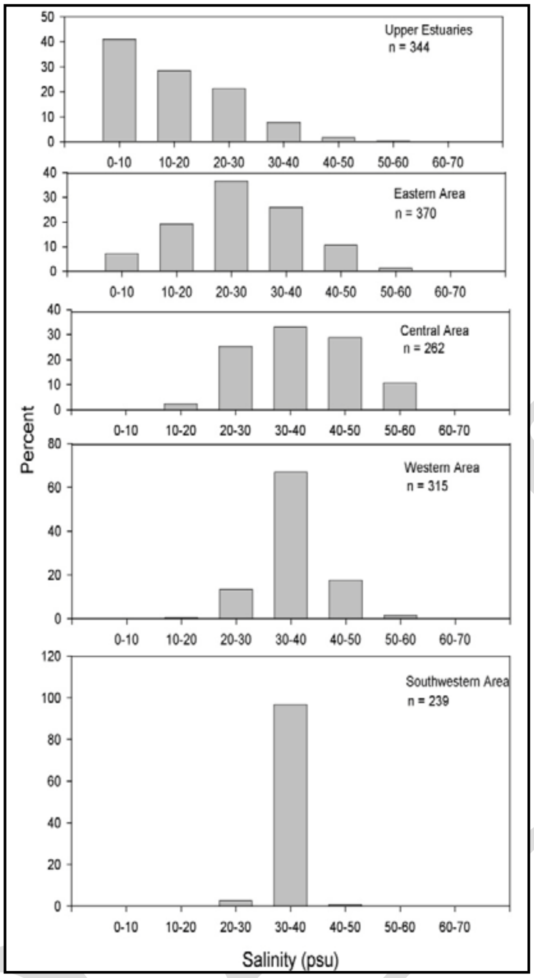


FIGURE 1-3: THE SALINITY DATABASE SYNTHESIZED IN ROBBLEE ET AL. (2001) EMPLOYS A BASIN GRID IN WHICH THE GRIDS ARE LOOSELY DEFINED AS HYDRO-DYNAMICALLY HOMOGENEOUS AREAS



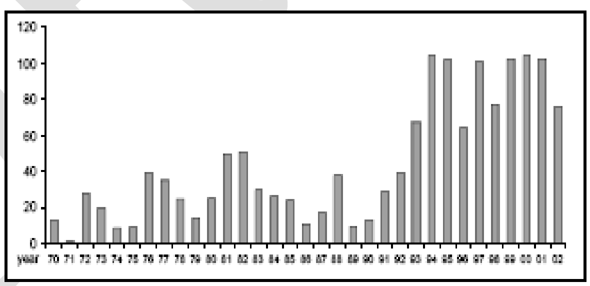
Source: Robblee, 2001

FIGURE 1-4: RAINFALL PATTERN IN FLORIDA BAY



Source: Robblee, 2001

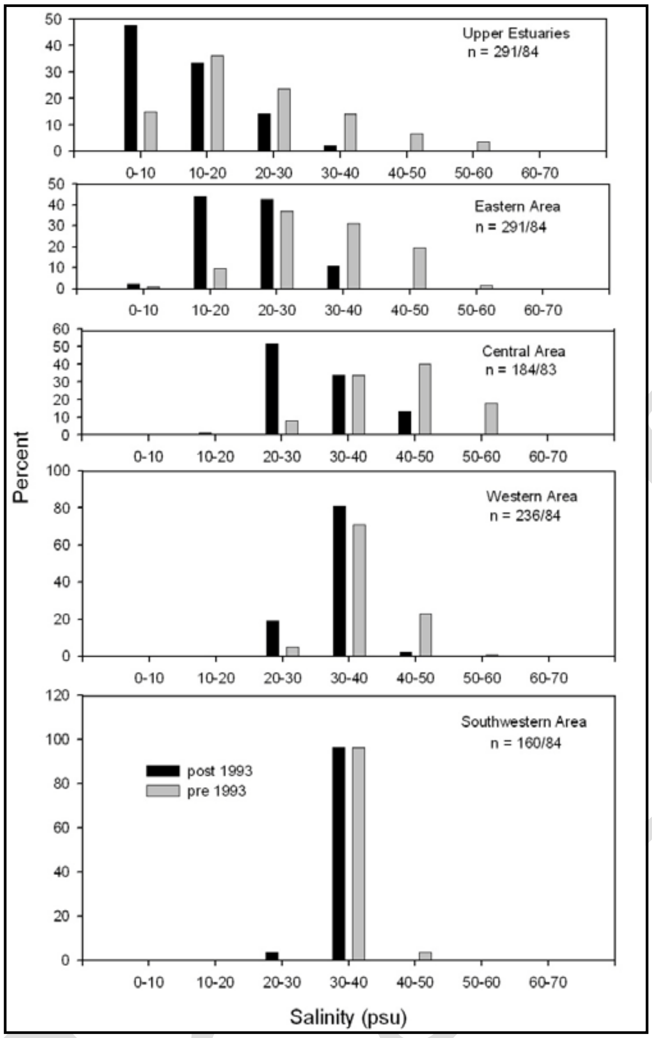
FIGURE 1-5: SALINITY PATTERNS IN REGIONS OF FLORIDA BAY 1955 -1999



Source: SFWMD, 2006

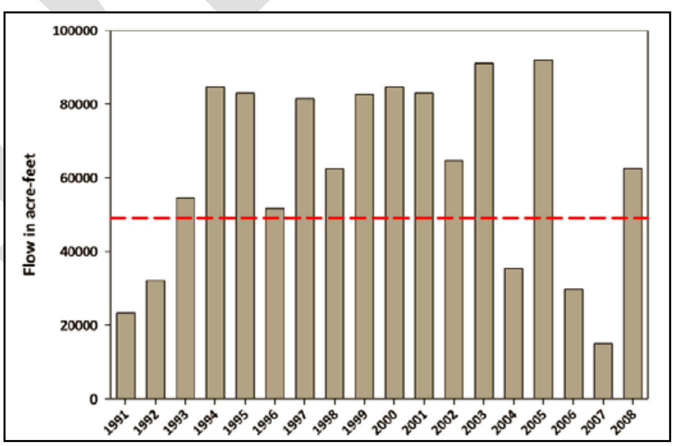
FIGURE 1-6: TIME SERIES OF ANNUAL FLOWS THROUGH TAYLOR SLOUGH BRIDGE FROM 1970 TO 2002 DEMONSTRATING THE INCREASE IN FLOW AFTER 1993

Figure 1-8 provides a continuation of flows after 2002. Flows in this graph are in 10^6 m^3/year; note that flows in ***Figure 1-8*** are in acre-feet/year.



Source: Robblee, 2001

FIGURE 1-7: COMPARISON OF THE PERCENT OF SALINITY WITHIN RANGES IN AREAS OF FLORIDA BAY BEFORE AND AFTER 1993



Source: Woods and Zucker, 2009

Note: The red line is the mean 25-year annual flow value.

FIGURE 1-8: ANNUAL FLOW AT TAYLOR SLOUGH BRIDGE IN EVERGLADES NATIONAL PARK.

1.3 System-wide Performance of Comprehensive Everglades Restoration Plan 2015: Results of the Band 1 Evaluation

The following is the Executive Summary of RECOVER's Technical Report on the System-wide Performance of CERP 2015 Band 1 Projects. The full document can be found at http://www.evergladesplan.org/pm/recover/band_1_report.aspx.

Authors: RECOVER Planning and Evaluation Teams
Contributing reviewers: The Band 1 Report was approved by the RECOVER Leadership Group on December 15, 2009 and signed by the CERP implementing agencies on May 28, 2010.

The Band 1[19] system-wide planning and evaluation effort took the first seven of ten conditionally authorized Comprehensive Everglades Restoration Plan (CERP) projects from the Water Resources Development Act (WRDA) of 2000 plus three other CERP Band 1 projects and modeled them using the South Florida Water Management Model (SFWMM). Evaluation of the model results revealed several important performance results to inform future CERP and non-CERP planning activities:

- Regional groupings of projects provide measurable predicted restoration benefits using Restoration Coordination and Verification (RECOVER) system-wide performance measures
- Using these groupings will help CERP staff evaluate major CERP project alternatives as part of the CERP project approval process
- Several opportunities exist to employ adaptive management as a part of system operations and long-term CERP implementation. Adaptive management provides the means to address uncertainties related to system-wide performance among multiple regional goals and objectives in order to optimize total system benefits.

In addition, the 2015 Band 1 projects revealed the following system-wide and regional performance trends:

- Damaging high flows in the Northern Estuaries were reduced
- High stages increased in Lake Okeechobee, impacting lake littoral zone health
- Extreme high water events were reduced in the southern portions of Loxahatchee National Wildlife Refuge and Water Conservation Area (WCA) 3A
- Extended periods of ponding continue to occur in southern WCA 2B
- Rotenberger Wildlife Management Area stages moved closer to the Natural System Model targets
- Overall inflow into the Everglades Protection Area increased by 138,000 acre-feet per year in the model, upon the assumption that water quality conditions were adequate
- Decreased inundation duration occurred in northern WCA 3, which reflects an increase in cumulative drought intensity

[19] The term "Band 1" stems from the Master Implementation Sequencing Plan (MISP) produced in 2005, and while it is acknowledged that the current effort on the Integrated Delivery Schedule supersedes the MISP, RECOVER's Planning Team has elected to retain the Band 1 nomenclature. Band 1 projects can be found on pages 2 and 3 of this report.

- As a result of the Broward County Water Preserve Area C-11 impoundment, S-9 pumping was reduced from 36,200 to 700 acre-feet per year, improving water quality in this area
- Everglades National Park (ENP) experienced longer inundation durations, which reflects a decrease in cumulative drought intensity
- Flow across Tamiami Trail into ENP increased by 176,000 acre-feet annually, primarily in the dry season
- Peak high salinities in the Southern Coastal Systems were reduced in duration and intensity
- Band 1 is projected to increase total water storage capacity by 466,990 acre-feet per year, which is nine percent of total reservoir and aquifer storage recovery storage planned for CERP. It should be noted that when the modeling was performed for the Band 1 effort, it was still presumed that the Everglades Agricultural Area (EAA) Reservoir Phase 1 (170,000 acre-feet) would be in place.
- Flood control results were mixed, and water supply cutbacks for the Lake Okeechobee and Lower East Coast Service Areas increased
-

The restoration program as a whole would benefit by the development and implementation of adaptive management system-wide strategies as part of the System Operating Manual Study to substantially improve CERP performance. This should accomplish the following:

- Help address Lake Okeechobee operations uncertainty associated with accomplishing multiple CERP goals and objectives
- Improve the ability to deliver water to coastal estuaries during the dry season while meeting multiple regional goals
- Couple the results of system-wide monitoring and assessment with integration of future projects that add significant water storage and delivery capacity to the regional system

In addition, planned future CERP and non-CERP projects are needed to build upon Band 1 performance. The Band 1 modeling clearly indicates the need for additional projects to capture, store and clean more water and for all water resource related needs. CERP system-wide planning (multi-project planning) activities, using groups of projects such as those used in this 2015 Band 1 analysis, provide a means to improve CERP plan formulation and project integration.

1.4 Role of Flow in Maintaining the Ridge and Slough Landscape

Author: Jed Redwine (USACE Contractor)
Contributing reviewers: Laurel Larsen (USGS), Kelly Keefe (USACE)

Since the publication of the Comprehensive Everglades Restoration Plan (CERP) in 1999 the role of flow in maintaining the ridge and slough landscape has received much attention. During the planning of CERP, water levels and volume exchanges between basins were focal metrics for expressing goals for the restored hydrologic system. The relationship between these hydrologic measures and ecological responses (like the development of ridge and slough habitats) was not fully understood, although landscape deterioration appeared correlated with areas where hydropatterns had changed the most.

Subsequent to the authorization of CERP, understanding the role of flow in Everglades restoration became a high priority for the south Florida science community and was addressed by the South Florida Ecosystem Restoration Task Force (SCT, 2003). Some key findings of the SCT review were that ongoing changes in the Everglades ridge and slough landscape are having detrimental ecological effects on Everglades biota (pg 1/62 of SCT 2003), and the degradation of the ridge and slough landscape suggests that "something more than hydrologic conveyance at discrete intervals is needed" (pg 15/62 of SCT 2003).

The SCT 2003 report gives a prioritized list of research questions and activities, which helped motivate the development of a ridge and slough habitat conceptual ecological model (Ogden, 2005), and regional and local scale research on flow. The research results suggest that the following flow-related factors affect ridge and slough elevations.

Prolonged inundation:

- Leads to the disruption of ridge and slough elevation pattern (Wu et al., 2006)
- Leads to disappearance of ecotones and drowning of sawgrass ridges in southern Water Conservation Area (WCA) 3A (Zweig and Kitchens, 2008, 2009)
- Occurs chronically only in areas directly upstream of impoundment structures (based on analysis conducted with EDEN datasets from 2000-2008 http://sofia.usgs.gov/eden/)

Overdrainage:

- Degrades the regularity of ridge and slough elevational pattern (Wu et al., 2006), by reducing the frequency of sloughs (Rutchey et al., 2005; SCT, 2003; Zweig and Kitchens, 2009).
- Occurs in the upstream areas of WCA 3, and throughout Everglades National Park (SCT, 2003)
- Increases the risk of peat consuming fires (Beckage et al., 2003 – paper is focused on climate variability influencing sea-level rise, but results are applicable to drainage)

Reduced water flow velocities caused by impoundment:

- In the existing areas of WCA 3A which are intact, Everglades wetland flows generally travel lees than 1 centimeter/second depending on vegetation, water depths typically range from 0 - 70 centimeters, and the flows are laminar to transitional (Harvey et al., 2009 [cites Riscassi and Shaffranek, 2004; Lee et al., 2004], Bazante et al., 2006; Harvey et al., 2005; Leonard et al., 2006).

- Flow velocities less than 3 centimeters per second do not suspend and transport of organic material particles from sloughs onto ridges (Harvey et al., 2005, 2009; Larsen et al., 2007, 2009a, 2009b, 2009c).

A set of findings about the physical properties of flow in intact ridge and slough habitats can be added to these specific findings about actual effects of flow in the ridge and slough habitat:

- Periphyton and Utricularia (or submerged aquatic vegetation [SAV]) exert greater control over flow characteristics of ridge and slough habitats than the identity (i.e., sawgrass or spike rush) or density of emergent macrophytes under the range of conditions observed by Leonard et al. (2006); however, over a broader array of historic hydrologic conditions, density and community type also become very important controls on flow (Larsen et al., 2009c; Harvey et al., 2009).
- Fluid dynamics of laminar-transitional flowing wetlands influence particle transport, phosphorus transport, nutrient cycling, and hydrologic-vegetation interactions (Harvey et al., 2009 cites Harvey et al., 2005; Huang et al., 2008; Larsen et al., 2007, 2009a, 2009b, 2009c; Leonard et al., 2006; Noe et al., 2003, 2007; Saiers et al., 2003).
- All classes of chemicals dissolved in the water column move about approximately 50 percent slower than the water moves, including phosphorus, mercury, and sulfate. Floating aquatic vegetation and the surficial soils are responsible for slowing their movement through the marsh (Leonard et al., 2006; Harvey et al., 2005 [cites Noe et al., 2002; Krabbenhoft et al., 1998; Bates et al., 2002]).
- Phosphorus-rich particles mostly consisted of suspended bacteria, suspended particles in Everglades wetlands were small in size and had low concentrations of phosphorus, yet they stored a large proportion of surface-water phosphorus in intermediately reactive forms. These suspended particles held little N (nitrogen) Noe et al. (2007).

These investigations suggest that the fluid dynamics of the ridge and slough influence solute movement through the marsh, and the biological supply-demand processes interact with the fluid dynamics to determine the resulting impact of nutrients in the ridge and slough habitats. This interaction may result in the development of a patterned landscape with healthy ridges and sloughs only if the habitat is sufficiently hydrated, deep water conditions are not prolonged, and flows exceed 3 centimeters per second with sufficient frequency. The threshold of sufficiency has not yet been defined, and the relative contribution of carbon that is redistributed from sloughs to ridges in forming a patterned landscape has not yet been determined.

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1.5 Evapotranspiration: A Link in the Hydrologic Cycle

Authors: Pam Latham (USACE Contractor), Kelly Keefe (USACE)
Contributing reviewer(s):

What is Evapotranspiration and why is it relevant to Everglades "new science"?
Evapotranspiration (ET) is a combination of water lost from a surface, such as soil, into the air (evaporation) combined with the loss of water from through living plants into the air (transpiration). The sum of evaporation and transpiration accounts for most of the water that moves from the earth's surface into the atmosphere. ET is an important part of Earth's water cycle: after water has fallen as rain or snow it eventually returns to the atmosphere by ET and then can fall again as rain or snow. ET plays a role in the Everglades because the ecosystem contains extensive wet, vegetated areas, which means that a significant amount of water evapotranspirates from the Everglades into the atmosphere; ET represents the largest loss of water from the system (Porter and Porter 2002). Such loss to the atmosphere may seem undesirable since restoration efforts aim to provide *more* water to many areas in the Everglades, but the losses to the atmosphere help to create the rain that replenishes and drives the system. ET is included in Everglades hydrology models such as the Natural System Model (NSM) and the South Florida Water Management Model (SFWMM or the "2x2"). New science on ET may affect how scientists, modelers, and decision makers consider ET in the models and how ET will be accommodated in restoration.

Evapotranspiration Measurement, Sources of Error, and Uncertainty
ET research began in the early 1900s in agriculture in arid regions such as southern California, Utah and Colorado, in response to the conversion of wetlands to agricultural production (Drexler et al., 2004). Since then, quantifying water budgets in wetlands, including ET, has become a focus. New science has emerged on estimating ET, correlations with ecosystem features, sources of measurement error, and changes in ET rates with climate change.

The Bowen ratio energy balance, Eddy correlation, Penman-Monteith combination equation, and the Priestley-Taylor approximation are the most common methods of estimating ET and can be adjusted to less than ideal conditions such as sloping terrain (Pauwels and Samson, 2006). There is a "Simple Method" of measuring ET (Abtew, 1996), which has been used alternately with the Penman-Monteith in the Everglades NSM and the SFWMM. There are recent promising improvements in ET estimates that use remote sensing and North American Regional Reanalysis data. Studies have been performed that outline the advantages and disadvantages of using remote sensing methods to estimate ET at a regional scale (German, 2000; Kite and Droogers, 2000; Anderson et al., 2003; Chen et al., 2005; Wang et al., 2007; and others). Ability to measure ET at a regional scale could improve estimations of ET in Everglades models.

Numerous studies have investigated the strength of relationships between ET and other parameters needed to estimate ET such as solar radiation or water depth, among others (Zhang et al. 2004, Hidalgo et al. 2005, Sumner and Jacobs 2005, Wang et al. 2007). The studies indicated that the relationships are complicated and therefore measures of ET can be very site-specific, making it difficult to generalize ET values over large areas. For example, Dunn and McKay (1995) found some parameters had a greater effect in lowlands than in uplands. Rim (2004) found that solar radiation was the most sensitive meteorological factor and wind speed was the least sensitive, and that ET sensitivity to humidity is less in the inland areas than in the coastal areas. Stoy et al. (2006) found that soil water supply was the principal external driver on inter-annual differences under wet conditions, while the leaf area index had a greater influence during drought conditions, and finally, that ET varied under wet and dry conditions for different ecosystems. The many factors that affect ET make generalizations difficult (Dunn and Mackay 1995; Hobbins et al., 2001; Anderson et al., 2003; Nordbotten et al., 2005; Stoy et al., 2006; Wilcox et al., 2006; Finnerty et al., 2009; others), which can in turn complicate the inclusion of ET in hydrological models. Both Breuer (2003) and Eckhardt et al. (2003) concluded that such uncertainties lead to uncertainty in models.

Although significant progress has been made in measuring ET, available data remain notorious for errors and biases from instrumentation design and calibration, errors in equipment operation, errors or biases in weather data used for ET calculations, poor conditions in measurement sites, and other factors (Allen 2000). Direct comparisons of ET (and therefore error) are difficult due to differences in climate, soils, land use, adjacent vegetation, and differences in scale among these. Field measurements are site specific and measurements between sites can vary at least as much as ET estimates made with different methods at the same site. Numerous individual studies have quantified ET at various scales, in different wetland systems, and with different methods, and compared results with other methods and studies and studies suggest an enormous natural range in ET variability just among wetlands. For example, ET reportedly accounts for 20 to 80 percent of the water loss in a wetland (Mitsch and Gosselink, 2000). ET "removes" a reported 50 percent of the water from rainfall in deep water with shallow rooted vegetation in sandy soils (Sumner, 1996), and almost 110 percent of the rainfall is subsequently lost to the atmosphere via ET in open water lakes (Swancar et al., 2000). Several authors (Mitsch and Gosselink, 1993; German, 2000; Abtew et al., 2003) report that the actual ET of wetlands in which water persists can be estimated as the theoretical atmospheric demand, or potential, ET of wetlands, although these measurements are affected strongly by surrounding vegetation, water depth, etc. and vary as well. Allen (2000) states that "as a conservative estimate, probably 3/4 of all ET data available have significant biases and errors that should (pre)clude them from being considered for use to calibrate mathematical models." In addition, annual ET in south Florida may increase up to 15 percent by 2099 compared to estimates from 100 years earlier, depending on climate change, adding further uncertainty to ET estimates and water management models that rely on ET estimates.

Several investigations and reviews of ET provide excellent sources of relevant ET data, analysis, and critiques, and should be reviewed by those interested (e.g. Kite and Drooger, 2000; German, 2000; Jacobs et al., 2002, Drexler et al., 2008; Douglas et al. 2009, Marshall et al. 2009,). Summary tables are available from Restoration Coordination and Verification (RECOVER) that present an overview of ET methods of measurement, estimation, error, scale, values for wetland plant species, suitability of different ET estimation methods for various applications, and a summary of the advantages and disadvantages of ET measurements and estimates for use in various types of wetlands.

Evapotranspiraton in Everglades Hydrology Models

Reviews of some Everglades hydrology models indicate that ET is a dominant process in the models that determines, in part, the projections of water moving through the system (Fennema et al., 1994; Bales et al., 1997; SFWMD, 2005). Similarly, a hydrologic model sensitivity analysis performed by Bahremand and DeSmedt (2007) concluded that of eight parameters examined, ET had the greatest sensitivity. Those involved with Everglades hydrology models recognize the difficulties associated with ET estimates and the importance of ET to the Comprehensive Everglades Restorataion Plan (CERP); each new version of the models attempts to clarify and improve the ET. The South Florida Water Management District (SFWMD) also continues to pursue more accurate ET measurements.

Conclusion

ET is a significant part of Everglades hydrology modeling, while many factors influence ET and its measurement. The wide variety of influences combined with the potential sources of measurement errors bring uncertainty to the estimates and therefore to the hydrology models. Good documentation can clarify the ET values included in hydrology models, and flexibility in wetland restoration planning and water storage capacity can accommodate for uncertainty in the estimates.

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1.6 Current and Projected Water Availability

At the heart of this topic is the question “How much water is available for restoration?” This topic could be a valuable addition to the Scientific Knowledge Gained (SKG) document but is a difficult one to tackle, and quickly diverts into a discussion of policy. A summary should include data and published research results, without statements on policy or values.

If you are available as an author or have an author to suggest, please include contact information on your comment form.

1.7 Water Storage and Delivery Technologies

The following topic summaries are under the heading "1.7 Water Storage and Delivery Technologies:"

- 1.7.1 Canal Backfilling and Restoration
- 1.7.2 Aquifer Storage and Recovery (ASR)
- 1.7.3 Reservoir Hydraulic Design
- 1.7.4 Recyclable Water Containment Areas – Using Ecosystem Services to Meet the Needs of the Agricultural Community and the Environment

1.7.1 Canal Backfilling and Restoration

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**Reviewed a much earlier version of this topic summary.*

Natural sheet-flow regimes in south Florida have been disrupted by canals and/or levees constructed as part of the Central and Southern Florida Flood Control (C&SF) Project. The natural ecosystem cannot be restored without undoing some of these alterations. This paper will present knowledge gained over the past ten years from the experience obtained on two Everglades restoration projects: Kissimmee River restoration and backfilling of the Prairie Canal. Information on the Kissimmee River has been extracted and condensed from a document that summarized lessons learned from backfilling of the C-38 Canal (RECOVER, 2005). Finally, lessons learned from the backfilling of canals in southern Louisiana used to support oil exploration are included in this paper.

Kissimmee River Restoration

Restoration of the Kissimmee River demonstrates how undoing the man-made physical changes to the landform are essential (filling the canal, removing the levees, removing water control structures, and reconnecting the meandering channels abandoned by the canal) such that the original flow regime can be restored (RECOVER, 2005). The Kissimmee River was channelized by the C-38 Canal, a massive canal designed to convey floodwaters from Lake Kissimmee to Lake Okeechobee. It cut through a meandering river bed and floodplain generally aligned with the direction of the overall gradient and landform. Paramount above all other technical issues, restoring the natural energy grade lines that correspond to the full spectrum of flow regimes became the key to understanding the natural system and the target for restoration. Restoring the proper energy grade lines assures that the water depth, flow rates, landform, vegetation flow resistance, and velocities are all kept in proper synchronicity and form a continuum over space and time. It was learned that the C-38 Canal causes such disruption to the natural energy gradient of the Kissimmee River that the canal had to be completely backfilled (length and depth) in order to eliminate its disruptive effects to sheet-flow and other natural (riverine) flow, especially during periods of lower flows which dominate the temporal spectrum. A number of experiments in the field and in scaled laboratory models proved the shortcomings of partially blocking the canal and formed a key basis for justifying the complete backfilling of the canal (Loftin, et al., 1990).

The best approach to backfilling was determined from laboratory and field tests and involved constructing a stable plug at the downstream end of the canal section being filled. The shape of the plug generally established the slope of the downstream face which is armored against erosion with rip rap sized for anticipated flow velocities (Loftin, et al., 1990). Backfilling proceeded upstream of the plug without further concern for erosion to the downstream limit (location of stable plug) of that construction phase. Spoil was generally found near the canal and was removed by power hoe, moving the material to the fill site (generally a short distance) by off-road trucks, and final placement by bulldozer. No compaction of spoil material was required.

Very localized water level controls were useful to keep earthmoving production rates high. This was typically accomplished by leaving a small berm between the spoil excavation area and the adjacent floodplain until most of the spoil was removed. The question of seeding newly filled areas proved unnecessary.

Picayune Prairie Canal Backfilling

A portion of the restoration plan for Picayune Strand was accomplished in 2007, with the backfilling of seven miles of Prairie Canal (SFWMD, 2009). The canal was filled with adjacent spoil and excess material originally taken from the canal that was recovered by leveling roads between Prairie Canal and Merritt Canal, which is the next canal to the west. Unlike the Kissimmee River, backfilling of Prairie Canal was completed with less formal design specifications. The construction approach used an existing road network for access to Prairie Canal, where a 100 foot plug was initially created at the end of each road. If additional spoil material was available, individual plugs were extended in both directions. The top of the plugs were at the natural grade of the surrounding land. The lengths of the plugs varied significantly depending on the availability of adjacent and nearby spoil, but well over half of the seven miles of canal was filled. The ends of the plugs were sloped to create littoral habitat and for human safety considerations. Additional infilling of the remaining pools was encouraged by placing large woody debris in the remaining open pools after vegetation that had been cleared from the spoil was burned and hauled to these pools. Subsequent growth of emergent and submerged vegetation will produce detritus that over time should provide an increasingly tight seal on the bottom and sides of these pools.

Partial hydrologic restoration in the vicinity of Prairie Canal has occurred, and it is expected to further increase when Merritt Canal is plugged, because this latter canal is still diverting upstream flows that should be traveling into the vicinity of Prairie Canal. The partial hydrologic restoration is evidenced by water level increases on the order of several feet since the canal was filled as compared to water levels in wells near Merritt Canal (SFWMD, 2009). Surface and groundwater drawdowns that extended over one mile from the canal during the wet season and for two to three miles during the dry season into Fakahatchee Strand Preserve State Park prior to backfill were dramatically reduced when the canal was plugged. However, the lower portion of the canal, which remains open to the coast, is still having some effect on Fakahatchee Strand water levels along this transect.

The two years of monitoring restoration effects on vegetation are insufficient to detect consistent patterns of change, because the plant communities have also been influenced by varying temporo-spatial environmental factors at the 30 monitoring plots, including the effect of differences in fire regimes, exotic plant invasion, herbivory, droughts, and wind damage from hurricanes (SFWMD, 2009). Given enough time, a significant response is expected in the restored area compared to nearby control sites. Prior to restoration, the vegetation within the canal footprint was dominated by exotics or nuisance natives, but with intensive control efforts following restoration, they are becoming difficult to find as the native community becomes established (SFWMD, 2009).

Southern Louisiana Canal Backfilling

Canals were cut through vast estuarine marshes for oil exploration purposes in the early 20th century and their restoration offer lessons applicable to the Comprehensive Everglades Restoration Plan (CERP) (Baustian et al., 2009; Baustian and Turner, 2006). In particular, monitoring results suggest the use of foreign substrates as backfill material can confound restoration and facilitate colonization of exotics and facultative species. Depending on the objectives of the restoration effort, plugging and shallowing a canal with available spoil was found to be sufficient to achieve restoration goals (canal in the study was filled 60%, but the amount of spoil available to use as fill is related to the age of the canal). If hydropattern restoration is the main goal of the project, rendering the canal and spoil areas hydrologically inert through plugging leaves deep water pools that would accrue sediment and eventually fill in. No matter the methodology used to backfill canals in southern Louisiana, elimination of the canal footprint can take over 20 years.

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1.7.2 Aquifer Storage and Recovery

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The Comprehensive Everglades Restoration Plan (CERP) Central and Southern Florida Project Comprehensive Review Study (Restudy) recommends the construction and operation of up to 333 Aquifer Storage and Recovery (ASR) wells located in clusters throughout south Florida accounting for approximately 70 percent of the CERP system-wide water storage capacity. The unprecedented scale of ASR in the Restudy has led to public concerns with the use of ASR as part of Everglades restoration. The concerns are centered on two major issues: the potential for groundwater and surfacewater quality degradation associated with ASR operations, and the possibility of inducing structural damage to the aquifer as a result of pumping pressures. To address public concerns, identify uncertainties, and review the potential for regional-scale ASR implementation in Florida, the South Florida Ecosystem Restoration Working Group formed the ASR Issue Team in September 1998. The ASR Issue Team in collaboration with the National Academies, National Research Council Committee on Restoration of the Greater Everglades Ecosystem (CROGEE) developed a series of reports between 1998 and 2002 that provided recommended actions specific to ASR implementation in south Florida (1-3). The intent of the list was to identify the additional information needed to reduce uncertainties surrounding implementation of ASR at a regional scale.

In response to the recommendations defined by the Working Group and the CROGEE, two related efforts were initiated: the ASR Regional Study, and associated Lake Okeechobee and Hillsboro ASR Pilot Projects. The following is a summation of knowledge gained since the Restudy on findings relevant to the feasibility of CERP ASR implementation.

Hydrogeologic Investigations

A collaborative effort was undertaken by the U.S. Geological Survey (USGS), Florida Geological Survey (FGS), the U.S. Army Corps of Engineers (USACE) and the South Florida Water Management District (SFWMD) to conduct a thorough review of available scientific literature on the hydrogeology of south Florida. The literature obtained has been compiled in a comprehensive ASR database available at http://www.evergladesplan.org/pm/projects/pdp_32_33_34_44_asr_combined.aspx#asr (4). A regional, synoptic survey of ground water quality was completed to characterize the upper portions of the Floridan Aquifer prior to ASR pilot site construction. Preparation and reporting of this data is in preparation (June Mirecki, personal communication). Seven test wells were constructed to evaluate the hydrogeologic framework at proposed ASR sites. Information collected at these sites has been used to establish baseline conditions prior to initiating pilot project cycle testing (5-13). The data collected has led to a more comprehensive understanding of water levels and water quality in the Floridan Aquifer, and serves as calibration of the regional groundwater flow and solute transport model (5).

Geophysical and Geotechnical Investigations

While drilling the test wells and exploratory wells at the proposed CERP pilot project sites, extensive geophysical logging was completed to gather data on a range of hydrogeologic parameters including porosity, fracture potential, and confinement, all of which have aided in the understanding of patterns of flow and suitability of specific areas for ASR wells (5). Two reports were completed to evaluate pressure-induced fracturing: A desk-top analysis (14) and a more detailed investigation based on geotechnical data from pilot site cores (15). These investigations concluded that there is a low risk for single-well ASR operations to induce fracturing of aquifer matrix (Suwannee Limestone and Ocala Limestone) under normal, permitted operating conditions. The geotechnical analysis (15) was conservative, in that fracturing conditions were evaluated with a factor of safety, so that minimum conditions to quantify fracturing were defined. These models will be further refined to permit the evaluation of pressure build-up around ASR systems that consist of multiple pumping wells.

To understand the location and direction of preferential flow in the Floridan Aquifer from a regional perspective, a lineament analysis was completed over the entire CERP footprint. This analysis linked topographic features and known geologic formations to map linear trends in limestone formations, identify potential existing fractures, and from this extrapolate the direction of groundwater flow (16). The Restudy proposed several ASR well clusters along the perimeter of Lake Okeechobee, however little was known of the hydrogeology beneath the lake. In 2007, a marine seismic reflection survey was conducted on Lake Okeechobee and found that the upper portion of the Floridan Aquifer is laterally continuous under the lake and relatively consistent with the characteristics of the surrounding area (17).

Geochemical Studies

In 2004, water chemistry data from 11 potable water ASR facilities in south Florida were compiled to characterize the changes in water quality that occur during ASR cycle testing. Major findings included evidence that concentrations of major dissolved constituents including sulfate, nitrate, and chloride do not exceed the permitted levels set by the Federal Safe Drinking Water Act (18). Geochemical mixing models were also developed that, using chloride as a tracer, found that mixing trends are site specific rather than uniform throughout the upper Floridan Aquifer (UFA) (19). A second report characterized major geochemical reactions that occur during the progress of each ASR cycle of recharge, storage, and recovery (19). Recharging the upper Floridan Aquifer with oxygenated surface water initiates pyrite oxidation, which releases trace metals into the aquifer. The mobility of trace elements (for example, iron, arsenic, and molybdenum) is controlled by evolution of the redox environment in the aquifer as the cycle test proceeds, from oxygen-rich recharge conditions, to sulfide-rich (oxygen-poor) native conditions. Preliminary data from cycles 1 and 2 at the Lake Okeechobee ASR pilot site suggest that geochemical conditions are favorable to limit arsenic mobility at this site.

In order to quantify trace metal mobilization processes under controlled laboratory conditions, the FGS conducted water –rock interaction tests under anoxic conditions, using limestone from many representative Florida limestone lithologies, including those at proposed ASR pilot sites. These cycle test experiments indicated that trace elements such as arsenic, are released when the pyrite is exposed to oxygenated water, but that arsenic can be captured by reactions with newly precipitated source water iron oxide minerals that form subsequently within the aquifer (20-21).

In the decade following the proposal to include regional ASR in the CERP, a significant amount of investigations were undertaken to understand the behavior and distribution of arsenic in the upper Floridan Aquifer. Studies by Kim et al. (2000), Price and Pichler (2006); and Jones and Pichler (2007) recognized that oxygenated surface waters when mixed with reduced native waters from the upper Floridan Aquifer mobilized arsenic from pyrite in the rock matrix (22-24). Jones et al. in 2007 utilized data from 19 upper Floridan Aquifer wells to develop a geochemical mixing model that again confirmed arsenic stability is lost upon mixing of surficial and native waters in the upper Floridan Aquifer and arsenic becomes mobilized into solution (24). Haque et al. (2006) found that that total arsenic concentrations were higher in ground water samples collected down-gradient from the recharge area of the upper Floridan Aquifer, indicating that arsenic can be mobilized through naturally occurring hydrologic processes (25).

Further implementation of all applications of ASR (potable and reclaimed water ASR by municipalities, for example) has been hindered due to the perception that regulatory compliance is exceedingly difficult. The Federal Safe Drinking Water Act and the Florida Administrative Code 62-550 (26) requires that arsenic concentrations not exceed 10 parts per billion (ppb) anywhere in a public water supply system or source of that system (for example, in an aquifer) (http://www.epa.gov/safewater/arsenic/index.html). However, within the last few years, data sets from ASR cycle tests have become more complete, which enables better interpretations of the geochemical conditions that control arsenic mobility. Nine ASR cycles have been completed at the Tampa-Rome Avenue Park potable water ASR system. The most important conclusion to be drawn from this data set is the consistent decline in maximum arsenic concentrations in recovered water samples, through cycles 4 through 9. A statistically valid set of trends were quantified at this site, leading to a statistical model that predicts during which cycle each ASR well will come into compliance with the state and federal drinking water regulations. To date, seven of eight wells show continuous improvement, and three wells are in compliance (27-28). Additionally, FGS bench-top studies in 2008 provided further evidence that decreases in peak arsenic concentrations were found with successive cycles of similar storage volumes measured at two existing ASR facilities in southwest Florida (29).

Ecotoxicology Analysis

As recommended by the CROGEE and required for Comprehensive Everglades Restoration Plan Regulation Act (CERPRA) and Florida Department of Environmental Protection (FDEP) regulatory compliance, extensive ecotoxicology investigations are being conducted as a component of the cycle testing at the Lake Okeechobee CERP ASR pilot project site (5). These investigations are intended to assess the potential of ASR recovered waters to impact acute and chronic toxicity levels and bioaccumulation of trace metals (for example arsenic, cadmium, selenium, and mercury) and radium in representative aquatic species native to surficial waters at and downstream of the ASR outflow locations. Initial toxicity bioassay series and acute static renewal definitive tests have been conducted at the Lake Okeechobee ASR Pilot Project with recovered cycle test waters. Initial findings have shown the recovered waters to have minimal impact on survival, reproduction, or embryo development in the representative fish, amphibian, and microorganisms tested (30). Ecotoxicology assessment will continue throughout cycle testing at the Lake Okeechobee pilot project site. Data will be incorporated into a conceptual ecological model (CEM) that will be used to conduct an ecological risk assessment of regional-scale ASR implementation.

Mercury Methylation Studies

Preliminary methyl mercury investigations indicate that methyl mercury levels in the UFA are low and not likely to result in direct ecological contamination via recovered waters (31).

Comprehensive Everglades Restoration Plan Aquifer Storage and Recovery Path Forward

Much of the information referenced above can be found in greater detail in the 2008 CERP ASR Interim Report (5). This information in combination with existing regional municipal well data and pilot project findings are being incorporated into a sophisticated, state-of-the-art groundwater model that will evaluate the need and feasibility of ASR on the scale proposed in the Restudy. The model will also be used to establish site selection and to determine to what level ASR operations are physically possible in south Florida within the limits of permit-driven water-quality requirements. The hydrologic output provided by the model, coupled with CERP Pilot Project cycle test water quality data, microbial studies, and ecotoxicology screening, will then be used to extrapolate the chemical and ecologic impacts of regional scale ASR operations in an Ecological Risk Assessment (5), which should be available by 2013.

Cycle testing at both CERP ASR pilot sites is continuing through at least 2011. Preliminary results thus far have been encouraging, including:

- Although arsenic has been detected in the aquifer during cycle testing, it appears that concentrations diminish through each cycle. Work is ongoing to quantify mechanisms that control arsenic mobilization.
- During Cycle 2 at the Kissimmee River ASR Pilot system, all recovered water returned to the Kissimmee River was in compliance with state and federal surface water quality criteria. The risk of rock fracturing at single-well ASR systems during typical, permitted operations is low. ASR cycle testing improves water-quality with respect to some constituents when recharge versus recovered waters are compared. Total phosphorus is reduced from approximately 50-100 to below 10 ppb in recovered water. Work is ongoing to establish the mechanisms that result in water-quality improvements.
- The regional ground water flow and solute transport model, supplemented by detailed inset models at sites proposed for ASR implementation, will define effects of ASR operations on ground water levels and solute transport.
- Ecotoxicology studies have shown the recovered waters have minimal impact on survival, reproduction, or embryo development in the representative fish, amphibian, and microorganisms tested.

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1.7.3 Reservoir Hydraulic Design

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Criteria--Federal and State

A. U.S. Army Corps of Engineers Approach-Progression

The primary U.S. Army Corps of Engineers (USACE) regulations governing the hydraulic design of dam and reservoir embankments are provided in Engineering Regulation (ER) 1110-8-2(FR). These regulations define minimum freeboard requirements based on risk standards and minimum Inflow Design Flood (IDF) routed storm events, including the inclusion of an antecedent-setting condition event. Other conditions/constraints were imposed on the designer with routing the IDF (e.g. gates are assumed inoperable during the event). Though the regulations provide for a requirement to review potential impacts of wind and wave action, it does not define what wind storm event should be utilized. There are several approved USACE Engineering Manuals (EMs) pertinent to hydraulic design of reservoirs that were used as guidance for Comprehensive Everglades Restoration Plan (CERP) projects. State of Florida regulations through the Florida Department of Environmental Protection (FDEP) Chapter 373 also provided guidance produced primarily for the mining industry, but are of limited use for the purpose of hydraulic design due to their general requirements.

B. Design Criteria Memorandums

With advent of the South Florida Water Management District (SFWMD) Acceler8 Program in 2004, SFWMD requested USACE participation in producing Design Criteria Memorandums (DCMs) that would provide same-design direction to future contractors in meeting both federal and state guidelines and requirements. The DCMs were specific in design approach by identifying criteria, parameter determination, and choice of numerical models for calculating hydraulic design data. The first three of the approximately 14 DCMs are directly connected with hydraulic design.

1. DCM-1 categorizes reservoirs using federal guidelines for assignment of the appropriate Hazard Potential Classification (HPC) of the structure.
2. DCM-2 covers the selection of the appropriate IDF and routing requirements based on the assigned HPC under DCM-1; and defines wind storm parameters and numerical models to be utilized in determining minimum embankment heights. This document does not provide an allowable overwash rate, thus final embankment height, as that is determined in the end through several avenues/disciplines of design analyses.
3. DCM-3 covers the design of overflow spillways used in compliance with DCM-2 routing requirements and reservoir drawdown criteria, i.e. low level discharge. Higher level discharges are a geotechnical concern requiring additional coordination with Hydrology and Hydraulics (H&H). DCM-3 provides the design approach and criteria for ensuring compliance with the Water Resources Development Act (WRDA 2000) Savings Clause. WRDA 2000 requires that projects do not significantly and adversely impact existing levels of flood protection.

C. State Approach-2009 versus 2010

DCM-2 and DCM-3 covers the design of spillways and storm(s) routing required that meet federal and state regulations. Prior to 2010, the DCM concept was to safely and cost effectively provide for lower embankment heights by managing storm events greater than 100-year floods with larger "gate" discharges than the state Environmental Resource Permitting (ERP) guidelines provide for during a 25-year storm event. However in 2010, upon SFWMD introspection in regards to managing extreme events with respect to potential flood-damage litigation, provision for large gate discharges in the DCMs is currently being modified. Potentially, this same issue may require the use of smaller auxiliary spillways, all of which would significantly increase the cost of CERP reservoirs implementation through requiring higher embankments.

Studies Complete/Needed

A. Allowed Overwash Rate

Perhaps the largest uncertainty in determining embankment height is how much overwash may be tolerated before an undesirable amount of damage occurs or imposes a higher risk by loss of integrity of the structure. Most guidances found through literature research is based on research performed by the Dutch, which may not be applicable or appropriate for south Florida site conditions. For instance, soil, vegetation, and duration of exposure are different for each reservoir site. Various measures to reduce overtopping have intrinsic benefits and shortcomings. On the waterside, overwash may be reduced by incorporating roughness, typically with stone riprap or steps, neither of which is beneficial to wildlife (use of vegetation on the waterside is impractical because of erosion). A shallow slope may assist in reducing impact, but at a high cost of construction due to increased fill volume required. In Florida, local riprap is limestone which has a low threshold of impact resistance over time. All structurally superior stone for riprap must be imported from northern Georgia and is very costly. This leaves two choices for embankment stabilization: smooth soil cement or stepped soil cement. Soil cement has a checkered history in Florida, demonstrated by the recent development of severe cracking in the Tampa Bay Reservoir. Another example of soil cement armoring is the Florida Power and Light (FP&L) reservoir in Martin County. The reservoir has been operating for nearly 30 years, but breached in 1979. Soil cement mixture, thickness and construction technique is critical for sound design.

- On the landside, the critical rate of overwash is dependent on soil composition and armoring, which is typically vegetative. The USACE Engineering Research and Development Center (ERDC and Mississippi Valley Division – New Orleans District/South Atlantic Division – Jacksonville District) is now researching Turf Reinforced Mat (TRM) that provides additional protection from overwash. TRM supports vegetation roots that resist surging overwash flow. Questions remain about the threshold of protection, maintenance aspects, and anchoring requirements. Other armoring is being investigated, including the use of soil cement and articulated concrete block (ACB). Soil cement on the landside has the same negative impacts as waterside usage. One benefit of ACB is that vegetation can grow through openings in the structure, however it is costly compared to other armoring systems.

B. Operations

Reservoir operations will be critical in optimizing project benefits. Creative operation protocols may prove cost effective. For example, the variable seasonal pool in Site 1 allowed for reduced embankment height. Site 1 is a prime example of adaptive management, as lessons learned are incorporated into its flexible operational plan.

C. Wildlife Entrapment and Reservoir Design

In a letter to the USACE dated January 26, 2009, the U.S. Fish and Wildlife Service (USFWS) documented wildlife usage and entrapment at the Ten Mile Creek Critical Project (TMCP) reservoir, located in St. Lucie County. Eighty-five species of birds were observed within the project area, 83 species of which are considered migratory. There were 13 ground-nesting bird species, ten species which successfully nested on site. Aquatic reptiles at the TMCP included five species of turtles, the American alligator, and various snakes.

The reservoir's interior embankment has wave-dissipating vertical steps which are impassible obstacles to wildlife. Vertical barriers prevent wildlife ingress or egress; and increase travel time and distance on the armored concrete embankment. Consequently, wildlife that is entrapped by vertical barriers suffer increased exposure to predation, heat stress, and plastron abrasion (in turtles) that frequently result in fatalities. Gradual, barrier-free, slopes are necessary for wildlife movement and survival in embankment reservoirs.

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1.7.4 Recyclable Water Containment Areas – Using Ecosystem Services to Meet the Needs of the Agricultural Community and the Environment

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In today's society environmental restoration and preservation often compete with human growth and development. Stemming from this challenge, there is growing interest in programs that provide compensation in return for ecosystem services (1). Various proposals have been put forth in Florida, one of which is the concept of Recyclable Water Containment Areas (RWCAs). RWCAs are temporary shallow water impoundments constructed on private crop lands that provide the south Florida community selected ecosystem services in exchange for compensation that would be less than that incurred if the state were to provide that service. For example, land purchase costs and subsequent state maintenance would be avoided, also keeping the land on the tax rolls and at the same time benefiting both society and the environment. This is a relatively new concept that has been proposed by the University of Florida, Southwest Florida Research and Education Center as a means of incorporating the agricultural community into regional environmental restoration efforts for mutual benefit (2). RWCAs have been proposed as a method of inland water storage and treatment as either an alternative or compliment to large scale above ground storage reservoirs for the purpose of water impoundment. Water stored in the RWCAs would not however be available for water supply or irrigation. An RWCA would operate as a contractual agreement between government agencies and members of the private sector. A similar program, the Florida Ranchlands Environmental Services Project (FRESP) (3), is already under development by the South Florida Water management District (SFWMD) for the Lake Okeechobee basin.

To function most effectively, water storage in a RWCA would be alternated with planted crops on a multi-year cycle. Once water has been stored for a predetermined period of time, the field would be returned to crop production. After a similar period of time, water again would be retained on the same field. In effect, water storage and related ecosystem services would become part of the crop rotation sequence used by growers. RWCAs would store non-urban run-off and stormwater drainage on laser leveled crop fields and, similar to standard agricultural impoundments, would be surrounded by a low perimeter berm and seepage ditch. Water within the impoundment would be retained at a depth of no greater than two feet and a weir structure feeding into a drainage system would bleed down excess water should the depth exceed two feet (2). Transplanting or seeding of wetland plants is encouraged to maximize the productivity of the retention area while inundated. Studies in 2002 indicated that vegetation in agricultural canals can be a major source of particulate phosphorus (P) loading to surrounding water bodies (4). One possibility to reduce this source of P while also stimulating the establishment of wetland habitat in the RWCAs is to relocate native aquatic vegetation from the surrounding canal system into the RWCA (2). Because the primary land use of the RWCA is agriculture, wetland plants would be removed before continuing with the normal crop rotation, providing a source of these plants for mitigation at other locations. While storing water, vegetation removed from canals could be disposed of in the RWCA to reclaim the nutrients from the unwanted vegetation.

Ecosystem Services Provided

When maintained properly, RWCAs provide a variety of ecosystem services. In return, the land owner through contractual agreement is provided compensation for the use of land and maintenance of the water storage area. The provided storage helps to slow flows to the coast, recharge groundwater, improve water and soil quality through nutrient sequestration and particulate settling, create temporary wetland habitat, and sequesters carbon in the form of senesced plant matter (5-6). To participate in an RWCA program, soil properties would have to be tested for elevated nutrient levels and deemed safe for water storage and capable of nutrient sorption (7).

Reducing total phosphorus (TP) in the hydrologic system is one of the greatest challenges facing ecosystem restoration efforts in south Florida. In inundated environments, P is removed through microbial and plant uptake and in alkaline solutions, through the process of $CaCO_3$ precipitation (8). In initial studies in the C-139 basin, an area southwest of Lake Okeechobee characterized by intensive agriculture, P sequestration in RWCAs was significant enough to completely alleviate the need for P fertilizer additives once the RWCA field was drained and returned to crop farming (4). Based on studies of the capacity of $CaCO_3$ to fix P from solution (9), it has been hypothesized that placement of crushed limestone within the perimeter berm of an RWCA could provide additional removal of P, and other charged particles such a copper, as retained water leaches through into the surrounding drainage ditch system. Once the water levels in an RWCA and surrounding drainage ditches recede in the dry season, the P saturated limestone within the berm could be retrieved and spread on surrounding crop fields as a soil amendment (5). As total maximum daily loads (TMDLs) are set for the Caloosahatchee Basin, RWCAs in the upper Basin could potentially be used for nutrient trading with downstream urban communities to meet TMDL requirements (5). Such an agreement is one plausible way in which a funding base could be generated for a regional RWCA network. The RWCAs would remain in private ownership for agricultural purposes. Nutrients and organic matter captured in the RWCAs would be used by subsequent cropping practices lowering fertilizer requirements. Additionally, having alternative income streams for growers provides for a more stable agricultural community rather than the single crop production market that currently exists. At the same time, removal of nutrients and related water storage would require smaller water treatment facilities for urban communities and partially decrease the need for large works of the SFWMD for water storage, both of which save societal costs while complying with TMDL requirements.

Diverting the first flush of stormwater into retention areas and allowing total loss to evapotranspiraton (ET) and infiltration has been shown to be one of the most effective agricultural best management practices (BMPs) for improving water quality, removing up to 95 percent of certain insoluble compounds (10). RWCAs are a viable means of capturing and storing this first flush water. Water stored in the RWCAs is not intended for use in water supply or irrigation. MIKE-SHE modeling in 2006 showed that shallow water storage in agricultural impoundments was reduced to levels below the minimum level for reuse within a few weeks of the start of the dry season, lost primarily to seepage and ET (11). Water in the RWCAs would be captured in the wet season and retained until lost to ET and lateral or downward infiltration during the dry season, providing recharge benefits to the surrounding water table while providing water and soil quality improvements (10).

Level of Local Interest

Approximately 75 percent of citrus farmlands in southwest Florida have acreage designated as agricultural impoundments (11) including approximately 16,000 acres of permitted stormwater retention areas in the Caloosahatchee Basin (12). It is possible that a significant portion of these permitted retention areas in combination with current crop lands could provide substantial water storage through a distributed network of RWCAs (4);, however, uncertainties regarding large scale use of RWCA's will need to be addressed on a programmatic level for implementation to be wide spread. In a November 2009 public meeting held in Immokalee to promote the concept of RWCAs, more than 100 members of the agricultural community in southwest Florida were in attendance and intense interest in the RWCA concept was expressed http://swfrec.ifas.ufl.edu/events/workshops/111009/. Although a relatively new concept requiring additional research, testing, economic planning, and risk analysis, RWCAs have the potential to provide significant benefit to both the community and the environment.

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2 SEEPAGE AND AQUIFERS: KNOWLEDGE GAINED

This section of the Scientific Knowledge Gained (SKG) document addresses the following component identified by the Committee for Independent Scientific Review of Everglades Restoration Progress (CISRERP) as critical for Everglades restoration (NRC, 2006; NRC, 2008):

> Barriers to the 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 Comprehensive Everglades Restoration Plan (CERP).

2.1 Surficial Aquifer System in South Florida

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Introduction to the Surficial Aquifer System

Beneath the Everglades is an extensive groundwater flow system in limestone and sand sediments comprising the Biscayne Aquifer and Gray Limestone Aquifer (Fish, 1988; Fish and Stewart, 1991; Reese and Cunningham, 2000). These are collectively known as the surficial aquifer system. The aquifers are highly transmissive, karstic, and with water quality sufficient for water supply. The Biscayne Aquifer, which underlies Miami-Dade County, Broward County, and eastern Palm Beach County, is an important source of groundwater flow to estuaries, such as Biscayne Bay and Florida Bay (SFWMD, 2008). The Biscayne Aquifer is unconfined and serves as the sole source of drinking water to over three million residents in south Florida. The Gray Limestone Aquifer is confined or semi-confined in its eastern extent, but unconfined in the west (Reese and Cunningham, 2000). Together the aquifers supply 95 percent of municipal water and 5 percent of agricultural water supplies in south Florida (Renken et al., 2005).

Development Changes the Groundwater Balance

A system of drainage canals constructed between 1910 and 1928 drained both the upper portion of the Biscayne Aquifer and the freshwater mound behind the coastal ridge (Renken, et al., 2005). This resulted in a significant decline in groundwater flow towards the ocean and, consequently, has allowed the inland migration of the saline interface during dry periods (Renken et al., 2005; SFWMD, 2008). Groundwater's role in the Everglades has changed, from a freshwater storage reservoir sustaining the Everglades ecosystem during dry periods to one with less storage and increasingly degraded water quality (Harvey and McCormick, 2009).

Aquifer Recharge

The surficial aquifer system is recharged throughout the year by direct rainfall, infiltration in the Everglades region, and seepage from canals conveying water eastward from the Everglades (Price and Swart, 2006). For the Biscayne Aquifer in urban areas, shallow groundwater above the deeper semi-confining layer is substantially affected by urban rainfall while deep groundwater below the semi-confining layer maintains a composition similar to that of Everglades water (Wilcox et al., 2003). Groundwater recharge and discharge vary cyclically in the interior wetlands of the central Everglades, driven by the differential responses of surface water and groundwater to annual, seasonal, and weekly trends in precipitation and operation of water-control structures (Harvey et al., 2004). A relatively thin (8 meters) layer of the 60 meter deep surficial aquifer actively exchanges surface water and ground water on a decadal timescale (Harvey et al., 2006).

Water Supply

The Biscayne Aquifer has traditionally been the source for water supply in southeast Florida. However, water utilities have begun to diversify water supply sources to include the deeper Upper Floridan Aquifer and have embarked on alternative water supply projects such as reuse (SFWMD, 2006). Increasing water reuse is intended to reduce competition with natural systems supplies and reduce dependence on sources recharged by the Everglades. Aquifers to the west of the Biscayne and beneath the Everglades generally have been ignored as potential sources of groundwater, both because of the lower transmissivities and because of the higher total dissolved solids in groundwater beneath the Everglades (Harvey et al., 2004).

Water Quality and Preferential Flow Paths

In the past several decades interactions between groundwater and surface water have increased as a result of water management, resulting in reduced storage of fresh, uncontaminated water in the shallow aquifer located directly beneath the Everglades and also beneath basins such as the Everglades Agricultural Area (EAA) that discharge directly into the Everglades. The contamination affecting shallow Everglades' groundwater comes both from above and below (Harvey and McCormick, 2008). Recharge from above is increasingly contaminating shallow groundwater with nutrients, sulfate, mercury, and other contaminants, while the increased vertical hydraulic gradients have contributed to upward transport of salts from the deeper aquifer (Harvey and McCormick, 2008). Aquifer tests suggest that the Biscayne Aquifer behaves as a dual-porosity medium with preferential flow paths that are likely to yield limited dilution of chemical constituents contaminating the aquifer from the surface (Renken et al., 2008; Shapiro et al., 2008). The dual porosity nature is formed by touching-vug porosity or conduit (i.e., cavernous) porosity that is of much larger dimensions than the aquifer's smaller inter-granular matrix porosity (Cunningham et al., 2004; 2006). The difficulties of accurately modeling groundwater flow in dual-porosity aquifers with preferential flow paths were explored by Chin et al. (2009). New capabilities have been added to the groundwater model MODFLOW-2005 to address the complexities of modeling in such conditions (Shoemaker et al., 2008).

Saltwater Intrusion

Along the coastlines of Everglades National Park, saltwater intrudes into the underlying unconfined aquifer as far inland as 8 to 30 kilometers from the coastline (Fitterman et al., 1999). Increased demand for freshwater has also facilitated saltwater intrusion into the aquifer system through extensive municipal pumping (Wilcox et al., 2003). These processes have resulted in increased brackish groundwater to discharge to the overlying freshwater of the Everglades (Price et al., 2008; Renken et al., 2005).

Aquifer Discharge to Coastal Zones

The exchange of groundwater between land and sea is a major component of the hydrologic cycle. This exchange, where terrestrial water mixed with sea water is discharged to coastal water bodies, is called submarine groundwater discharge (SGD). Biologists have recognized that SGD provides important fluxes of nutrients, carbon, and metals to coastal waters (Moore, 2010). To emphasize the importance of geochemical reactions and mixing that occurs in these zones, they have been named subterranean estuaries (Moore, 1999). A similar term, coastal groundwater discharge (CGD), has been suggested to describe areas where brackish groundwater is to discharge to the surface waters of coastal wetlands (Price, et al., 2006). The occurrence of CGD associated with seawater intrusion has been identified in the southern Everglades (Price et al., 2006).

Groundwater and Biscayne Bay

Historically, the southern Everglades, Biscayne Bay, and Florida Bay were part of a larger hydrologically connected system of wetlands, tidal creeks, and coastal lagoons underlain by the

Biscayne Aquifer. During the past century, the hydrology of the Biscayne Bay watershed has been highly modified for agricultural, urban, and commercial development, including recreational use (SFWMD, 2008). The western advance of the saltwater intrusion front in groundwater and the channelization of surface flows by canals in Biscayne Bay have reduced the groundwater flowing from springs into Biscayne Bay and altered the estuarine zone (SFWMD, 2008). Currently, the two most important mechanisms for fresh water discharge to Biscayne Bay are thought to be canal discharges and submarine groundwater discharge from the Biscayne Aquifer (Langevin and Wang, 2007). Near-shore biological zonation in the shallow Biscayne Bay estuary is directly related to upward seepage of fresh groundwater. Groundwater discharge may also be partially responsible for nutrient loading or pollutant contamination to coastal marine estuaries (Langevin, 2003).

Recently, models have been created to determine the contribution of freshwater contributions to Biscayne Bay (Stalker et al., 2009). Stalker et al. (2009) showed a freshwater input ratio of canal/precipitation/groundwater of 37%:53%:10% in the wet season and 40%:55%:5% in the dry season with an error of ±25%. Fresh and brackish groundwater discharges to Biscayne Bay along the coastline and into the tidal portions of the Miami, Coral Gables, and Snapper Creek Canals. The average rate of fresh groundwater discharge is approximately3.7 x 10^5 m^3/day for the coastline of Biscayne Bay, about 1.8 x 10^5 m^3/day for the tidal portion of the Miami Canal, approximately1.4 x 10^5 m^3/day for the tidal portion of the Coral Gables Canal, and approximately 3.4 x 10^4 m^3/day for the tidal portion of the Snapper Creek Canal. (Langevin, 2003)

Groundwater and Florida Bay

The Everglades and Florida Bay ecosystem are closely linked by marine and freshwater hydrologic cycles. In addition to the freshwater discharges from Shark River Slough and Taylor Slough, the two major surface water outlets from the Everglades, substantial freshwater inputs to the northeastern section of Florida Bay are via groundwater (Smith et al., 1988). However, SGD into Florida Bay remains one of the least understood components of the regional water balance and is not represented in existing hydrodynamic models of Florida Bay(e.g., HYCOM and others) (Swarzenski, 2009). Groundwater represents a significant pathway for nutrients and other dissolved solutes into Florida Bay (Corbett et al., 1999). The contribution of nutrients from groundwater appears to be at least on the same magnitude as the estimated freshwater resources from the Everglades to the eastern part of the bay because Florida Bay is the estuary most influenced by hydrological and other anthropogenic modifications made in the southern Everglades watershed (Mclvor et al., 1994).

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2.2 Seepage Management: Advances and Challenges

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A key element of Everglades restoration projects that allow additional flows and longer hydroperiods in the Everglades Protection Area (EPA) is managing existing and increased future groundwater seepage. Groundwater flows from the EPA south and east to the coast with a hydraulic gradient of 0.00005 (Price and Stewart, 2006). Surface water in the EPA is directly connected to the groundwater due to the very high transmissivity of the karst substrates that define the surficial Biscayne Aquifer (0-90 feet below surface) (Krupa et al., 2008). Therefore, any increase in surface water stage in the EPA, and any changes in operational surface water levels east or south of the EPA, rock-mining lakes, and/or increased pumpages from the urban area would have a direct influence on groundwater flows due to the changing hydraulic head between the EPA and the urban corridor. The Restudy called for seepage management projects between the EPA and the developed Lower East Coast (LEC) to conserve water for restoration to the west and preserve levels of flood protection to the LEC and water supply demands to the east. Thus, a fine target has been set for seepage management projects that are dependent on the existing conditions, the magnitude of new water deliveries, and accurate estimates of associated seepage on the eastern border of the EPA.

Developing accurate estimates of seepage based on water table elevations has been the focus of several investigations over the past 30 years. Many investigators have used the traditional Darcian flow to estimate the regional seepage. Recent work, however, indicates that the accuracy of the well surveys (thus the elevation of the water levels in the wells) and survey uncertainty between stations might possibly be misleading. Widely varying estimates of hydraulic conductivity (K-values) of the Biscayne Aquifer confound efforts to accurately model the long eastern border of the EPA (Renken et al., 2005). Fish and Stewart (1991) report Biscayne Aquifer K-values between 13,750 feet per day and 36,250 feet per day. A recent study on preferential flow zones in the Biscayne Aquifer report K-values as high as 16,400,000 feet per day (Shoemaker et al., 2008). On the other hand, Nemeth et al. (2000) reported a K-value of at least 20,000 feet per day in a high conductivity layer of the Biscayne Aquifer. A modified drawdown test at the Comprehensive Everglades Restoration Plan (CERP) seepage management pilot project site along the L-30 (north of Tamiami Trail), typically thought of as the most transmissive site along the EPA border (C&SF, 1960), revealed a depth-weighted average K-value of 91,000 feet per day. Other estimates of a depth-weighted average at other sites include 17,000 feet per day (Fish and Stewart, 1991), 17,500 feet per day (Nemeth et al., 2000), 12,500 feet per day (Reese and Wacker, 2007). Further complicating the issues, recent work by Kevin Cunningham and Mike Wacker (U.S. Geological Survey) has shown that within Biscayne Aquifer there exists three type of flow systems: matrix porosity (area of Darcian flow), touching vuggys, and conduit porosity (Cunningham et al, 2006b). The definition described above has provided support for the disparities of K-values, both temporal and spatial (horizontally and vertically), within the cavernous groundwater system of south Florida. Additionally, evidence exists that groundwater flow may exhibit turbulent behaviors in some circumstances (Shoemaker et al., 2008; Kuniansky et al., 2008).

As part of the overall CERP efforts, better survey control on regional and site specific bench marks has given investigators a better understanding of the flow regimes and has enabled investigators to better assess the movement and uncertainty of groundwater flow to the coast.

CERP's ability to plan for managing seepage effectively while providing flood control and water supply to the LEC and Biscayne Bay is limited by the ability to model groundwater dynamics accurately under a variety of scenarios. Planning for the Everglades National Park Seepage Management Project (ENPSM) was suspended due to unacceptable levels of uncertainty about the hydrogeology of the seven-mile project transect and future hydrologic conditions (USACE, 2009b). Water delivery projects such as Modified Water Deliveries (ModWaters), Decompartmentalization (Decomp), and other water storage projects north of the EPA were too early in their planning process to quantify the flows into the Everglades National Park to be managed. In another example, the Big Cypress Water Conservation Plan has experienced major delays due to inadequate hydrogeologic data. Methodologies employed for the hydrogeologic investigation did not sufficiently reduce seepage uncertainties. The result is a $20 million basin (similar to a stormwater treatment area [STA]) that does not hold water for a sufficient period of time to meet the primary goal of the structure, although some other types of benefits are yielded like flood control.

Another uncertainty surrounds the proportion of seepage losses to canals, rock-mining lakes, wellfields, and the downstream aquifer (Wilcox et al., 2004). The border of the EPA and LEC is delineated with canals that provide water supply to agriculture in the Homestead area. If the amount of new water deliveries can be conserved by simply preventing seepage driven by hydraulic heads between the EPA and the urban area, then management projects can plan accordingly.

The L-31N Seepage Management Pilot Project (SMPP) should shed some light. Construction of the pilot project is scheduled for completion in March 2011 and will be tested for two years. The primary objective of the pilot is to reduce uncertainties regarding groundwater dynamics in baseline conditions, a passive seepage mode, and an active, reactive seepage management mode (USACE, 2009a). The pilot tests the effects of a seepage barrier that extends through the full depth of the aquifer. The barrier will be installed with an open window to allow some flow to pass through. Flows will be measured around the wall and in the window during wet and dry seasons to assess the proportion of seepage managed passively under various scenarios. Additionally, injection wells are housed in the window. When turned on, the window will effectively close, which will test the ability to actively manage seepage during wet periods when groundwater recharge can occur locally in the LEC. The end product of the pilot should be a more sophisticated understanding of groundwater dynamics under a variety of situations, a more accurate model for full-scale seepage management planning purposes, and an idea of the cost and effectiveness of several management measures (USACE, 2009a).

Another pilot is being conducted opposite the Rinker rock mine along the L-31N to test a passive, partially-penetrating seepage barrier. The monitoring network is similar to the proposed one on the L-30. This pilot is currently being tested, and results should be forthcoming this year.

While a great deal of uncertainty still remains, those involved in modeling and managing seepage have at least identified those uncertainties and are in the process of reducing them. The above mentioned pilot projects, combined with thorough mapping of high-permeability flow zones using a combination of borehole geophysical logs and cyclostratigraphic investigations (Cunningham et al., 2006), should allow planners of full-scale seepage management projects the tools to develop reasonable alternatives.

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3 EVERGLADES WATER QUALITY: KNOWLEDGE GAINED

This section of the Knowledge Gained document addresses the following component identified by the Committee for Independent Scientific Review of Everglades Restoration Progress (CISRERP) as critical for Everglades restoration (NRC, 2006; NRC, 2008):

> 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.

3.1 Ecological Impacts of Water Quality

The following topic summaries are under the heading “3.1 Ecological Impacts of Water Quality”:

- 3.1.1 Nutrients in Lake Ecosystems: Lake Okeechobee Sediments
- 3.1.2 Nutrients in Marsh Ecosystems: Phosphorus
- 3.1.3 Nutrients in Estuarine Ecosystems: Algal Blooms
- 3.1.4 Periphyton-Water Quality Relationships
- 3.1.5 Mercury in the Everglades
- 3.1.6 Sulfur in the Everglades
- 3.1.7 Copper in the Everglades: Contamination of Florida Apple Snails
- 3.1.8 Other Contaminants in the Everglades

3.1.1 Nutrients in Lake Ecosystems: Lake Okeechobee Sediments

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Sediments and sediment water interactions significantly affect the Lake Okeechobee environment. In the upper ten centimeters (cm) of sediments, the mass of phosphorus (P) is estimated at 2,870 metric tons with 42 percent of this in easily re-suspended mud sediments (Reddy *et al.*, 1995). In particular the mud sediments contribute to both turbidity and P concentration within Lake Okeechobee. P is affected through processes of accumulation and release to/from the sediments. A large amount of P has accumulated in lake sediments over the past century (Brezonik and Engstrom, 1998), but the accumulation rate has declined in recent years as the sorptive sites within the sediments have been filled (Havens and James, 2005; McCormick *et al.*, 2010).

Lead (^{210}Pb) dating studies estimated the accumulation of 600 g sediment/m^2/year and 850 mg P/m^2/year into the mud sediments of Lake Okeechobee (Brezonik and Engstrom, 1998). These equate to an average accumulation of 458,000 metric tons of solids per year and 644 metric tons of P per year in the Lake Okeechobee sediments. To verify these ^{210}Pb studies, other markers were measured for comparison. These included heavy metals, cesium (^{137}Cs), Polychlorinated biphenyls (PCBs), fertilizer contaminants, and pollen (Engstrom *et al.*, 2006; Schottler and Engstrom, 2006). All of these independent markers were reasonably consistent with the ^{210}Pb dating of the sediment, indicating the efficacy of this method. These studies were conducted prior to the 2004 and 2005 hurricanes (see below).

Internal loading primarily through diffusion from the sediments to the water column is approximately equivalent to external loads to Lake Okeechobee (Fisher *et al.*, 2005). A simulated dredging study on sediment cores found that dredging approximately 50 cm of the mud sediments would substantially reduce this internal load (Reddy *et al.*, 2006).

An engineering study of sediment management alternatives for Lake Okeechobee was initiated in 2000 (Blasland, Bouck and Lee Inc., 2001). The study concluded that dredging was not a feasible option based on high cost and estimated low effectiveness. Another option was to add chemicals to bind the P in the sediments (Blasland Bouck and Lee Inc., 2003). However, unless the external loads are reduced to appropriate levels (e.g., the Lake Okeechobee total phosphorus [TP] total maximum daily load [TMDL] [Florida Department of Environmental Protection {FDEP} 2001]), any sediment management activities undertaken to reduce internal loads would have to be redone in the future. The major recommendation of the sediment management study was to reduce external loads to Lake Okeechobee from the watershed.

In the past decade, Lake Okeechobee has been influenced directly by a number of hurricanes: Irene in 2000 (Havens *et al.*, 2001), Frances and Jeanne in 2004, and Wilma in 2005 (James *et al.*, 2008). Hurricane Irene was a weak storm that led to a number of changes in the water quality of Lake Okeechobee (Havens *et al.*, 2001). These included increased nutrient concentrations and turbidity as well as reduced light conditions. All of these changes were attributed to the re-suspension of mud sediments. The hurricanes in 2004 and 2005 were more intense and in the case of Frances, affected Lake Okeechobee for a much longer time period. The 2004 and 2005 hurricanes resulted in higher nutrient concentrations and turbidity, lower light conditions that continued for over two years (James *et al.*, 2008). To assess changes in the sediments after the hurricane, Balance Environmental Management (BEM) and the University of Florida remapped Lake Okeechobee sediments and sediment nutrients (BEM and University of Florida, 2007). Compared to previous mapping studies (Fisher *et al.*, 2001), there was a significant reduction of average mud sediment thickness in Lake Okeechobee, which was attributed to mud sediments being spread throughout the lake.

Another ^{210}Pb study on sediment cores from the center of Lake Okeechobee after the 2004 and 2005 hurricanes showed that the sediment layers were sequentially disturbed (Chang, *et al.*, 2008). Hurricane Frances and Jeanne mixed sediment layers as deep as 10-12 cm. Hurricane Wilma mixed the sediment layers from 10-12 cm up to 25 cm. Almost one-third of the sediment bed was re-suspended during these hurricanes, resulting in the increased total suspended solids as mentioned above. These sediments are now less consolidated and more easily re-suspended than before these hurricanes.

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3.1.2 Nutrients in Marsh Ecosystems: Phosphorus

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Everglades water quality summaries appear every year in the South Florida Environmental Report. These summaries are divided into distinct reporting periods: baseline conditions prior to best management practice (BMP) implementation and stormwater treatment area (STA) operation (1979-1993), first phase of BMP and STA operation (1994-2004), and current, i.e., post 2005 operations. Overall total phosphorus (TP) loads to the Everglades were significantly reduced in phase 1 compared to the baseline period. The phosphorus (P)-removal efficacy of BMPs and STAs is apparent as TP loads decrease in portions of the Everglades, despite increased flows observed in the same areas (SFER, 2009). However, there is significant interannual variability in surface water loads to the Everglades Protection Area; for example TP loads averaged 173, 94, 37 and 65 metric tons (mT) for water years 2006-2009, respectively. The high interannual variability in TP loads has been attributed to wide ranging climatic conditions, including several recent drought years, which results in soil oxidation and P release, as well as varying flow volumes. In contrast, during water years 2005-2006 tropical activity, including hurricanes, not only brought intense rainfall, but also caused damage to STA vegetation and subsequently reduced nutrient uptake for an extended time period (SFER, 2010). Geometric mean TP concentrations in inflow surface waters consistently decreased in Water Conservation Area (WCA) 2 and 3 over the three time periods. In contrast, while decreased inflow mean TP concentrations were observed in WCA 1 (Arthur R. Marshall Loxahatchee National Wildlife Refuge) and Everglades National Park from the baseline to phase 1 reporting periods, mean concentrations increased post 2005 in both areas.

Despite the reduction in TP loads to the Everglades, inflow TP concentrations are consistently elevated compared to unenriched areas of the ecosystem. During water years 2005-2009, inflow mean TP concentrations into the Refuge, WCA 2A, WCA 3A and Everglades National Park were 90, 31, 34 and 10 parts per billion respectively (SFER, 2010). This likely contributes to the continued expansion of P enriched areas within the Everglades interior. Spatial comparisons of soils (0-10 centimeters) collected during 1995 and 2005 indicated that in 1995, 34 percent of Everglades soils had TP concentrations greater than 400 milligrams per kilogram (mg/kg) (Comprehensive Everglades Restoration Plan's [CERP's] restoration goal), compared to 49 percent in 2005 (Scheidt and Kalla, 2007). In terms of area defined as impacted by the State of Florida, more than 500 mg/kg (Florida Administrative Code 62-302.540), the soil TP concentrations indicated P enrichment areas of 16 and 24 percent in 1995-6 and 2005, respectively. Similarly, more spatially intensive regional studies comparing 1991-1992 data with 2003 data indicated further penetration of TP from the western perimeter to the interior of WCA 1 (Marchant et al., 2009) as well as WCA 3 (Bruland et al., 2007). While DeBusk et al. (2001) demonstrated an increase in surface concentrations in WCA 2A in 1998 compared to 1990, Rivero et al. (2007) suggested that the percent area greater than 500 mg/kg may have decreased in 2003. It appears that floc mobility may be influencing this relationship (Marchant et al., in prep). Cattail cover, a highly visible indicator of nutrient enrichment, was mapped in WCA 2A in 1991, 1995 and 2003. Analysis of the data showed that cattail distribution continued to increase through 2003, however the rate of expansion decreased from 961 hectares (ha) from 1991 to 1995 to 312 ha from 1995 to 2003 (Rutchey et al., 2008). Recent reports also document cattail expansion and possible soil TP enrichment in Taylor Slough (Surratt et al., in prep). Regardless of the exact spatial extent of nutrient enrichment in the Everglades, legacy and continuing P enrichment will have significant effects on periphyton and plant community growth, composition and nutrient cycling for decades to come.

In summary, P enrichment of the Everglades has expanded further since publication of the Restudy in 1999. Significant reductions in nutrient loads to the ecosystem have been obtained since the implementation of BMPs and STAs; however, P enrichment, both from legacy and present sources, is a key issue that would influence future recovery.

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3.1.3 Nutrients in Estuarine Ecosystems: Algal Blooms

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While they are a naturally occurring phenomenon, phytoplankton blooms (also known as algal blooms) can be problematic. The definition of a bloom varies from estuary to estuary and with the parameter used to quantify phytoplankton (e.g., cell counts, biovolume, carbon or chlorophyll *a*). Nevertheless, a bloom occurs when the accumulation of phytoplankton exceeds a threshold. If these blooms become too large, the decay of the biomass can deplete dissolved oxygen, resulting in numerous ecosystem level effects associated with hypoxia and anoxia. In shallow habitats, blooms may shade seagrasses and other submerged aquatic vegetation (SAV) causing reduced growth and eventual mortality. The major bloom forming phytoplankter can also have large ecological consequences as some species produce a toxin that may cause mortality of various organisms (e.g., fish kills associated with red tide blooms) and others produce a mucilaginous mass that clogs filter-feeding sponges resulting in bloom propagation (Phlips *et al*., 1999).

This review is not exhaustive. Rather it will highlight recent information from estuaries in south Florida concentrating on what has been learned about nutrient limitation and sources, red tides, community composition and the use of chlorophyll *a* as an indicator of system status.

Nutrient Limitation

In south Florida estuaries, the macro-nutrient most likely to become limiting to phytoplankton, shifts from nitrogen (N) to phosphorus (P) along a North-South gradient (Bennett *et al*., 2003; Boyer, 2006). This gradient in nutrient limitation also occurs along the West Florida Shelf in the Gulf of Mexico from Sanibel Island in the north to Florida Bay in the south (Heil *et al*., 2007). Recent nutrient addition bioassay conducted in two northern estuaries, the St. Lucie (Phlips 2008; Yang *et al*., 2008; Lin *et al*., 2008) and Caloosahatchee (Loh, 2008a), indicate nitrogen limitation as expected. The drivers of this North-South gradient appear to include a transition from alumino-silicate sediments in the north to carbonate sediments in the south that bind and sequester P. In northern estuaries, much of the land derived P load is inorganic and available, while the N load is organic and not quite so labile (Doering and Chamberlain, 1999). During a dry season study, Loh (2008b) found that DON from the Caloosahatchee Estuary did not appear susceptible to attack by estuarine bacteria. In addition, the P concentration in some rivers (e.g., Peace River) is enhanced by P mining in the watershed (Heil *et al*., 2007). To the south in Florida Bay, Tomas (1999) demonstrated that phytoplankton blooms were P limited in eastern Florida Bay and N limited in the western bay.

Nuisance Blooms

In Florida, red tides are caused by blooms of the dinoflagellate, *Karenia brevis*. While blooms occur on both coasts of Florida, the blooms are more frequent on the west coast, especially off Sanibel Island (Lee County). At issue have been the sources of nutrients that fuel these blooms and whether the frequency and magnitude of blooms have increased over time. Vargo *et al*. (2008) estimated the contribution of several nutrient sources to sustaining a *Karenia* bloom (greater than 10^6 cell/l) on the central West Florida Shelf. No source by itself could sustain a bloom of greater than 10^6 cell/l. Atmospheric deposition, benthic flux, and nitrogen fixation by the cyanobacterium, *Trichodesmium*, were all minor sources. Zooplankton excretion was significant at times, but since these nutrients are recycled they do not add new biomass. Remineralization of dead fish could be a significant source, but rates are poorly known. The flux of nutrients from major coastal estuaries was variable but significant, supplying 11 to 50 percent of the maintenance nutrient requirement (Vargo *et al*., 2008). Yentsch *et al*. (2008) and Heil *et al*. (2007) both emphasized the role of coastal rivers in sustaining red tides. Importantly, Heil *et al*. (2007) noted that while riverine input may sustain a bloom, it is doubtful that nutrients in river discharge initiate blooms, as blooms begin far offshore away from terrestrial influence.

Brand and Compton (2007) analyzed historical data collected on the West Florida Shelf between 1954 and 2002. *Karenia brevis* generally was found to be more abundant inshore than offshore, and more abundant during the 1994-2002 period than earlier (1954-1963). These patterns are attributed to an increased availability of nutrients.

Although not damaging to human health, the southern part of the system experiences nuisance blooms that can cause a cascade of ecological degradation (Butler *et al*., 1995). These blooms are typically formed by the cyanobacterial, *Synechococcus* sp.; however, an important exception was the black-water event that garnered significant public attention. This bloom was composed primarily of diatoms. These nuisance blooms often damage benthic species leading to sediment de-stabilization, increased benthic shading, and increased nutrient re-suspension. This results in the creation of a positive feedback loop that can allow these blooms to persist for years in areas with restricted circulation (RECOVER, 2010). While the factors that initiate nuisance blooms are not always fully identifiable, a 2005 bloom in eastern Florida Bay suggests that inception may be, at least in part, event driven. Hurricanes likely played an important role here (RECOVER, 2010).

Community Composition

Phytoplankton community structure varies spatially and temporally in south Florida estuaries and coastal waters. Along with the nutrient limitation gradient noted by Heil *et al*. (2007), they found that *Karenia brevis* dominated in the N limited waters to the north (Sanibel Island), cyanobacteria in a mid–region, diatoms in western Florida Bay, and cyanobacteria in central Florida Bay (Phlips *et al*., 1996). Millie *et al*. (2004) studied phytoplankton in the lower North Fork of the St. Lucie and identified seasonal changes in community composition. Cyanobacterial picoplankton were abundant in summer, and these where eclipsed by golden algae (chrysophytes) in the winter. Diatoms where abundant in both seasons with cell carbon being dominated by *Skeletonema costatum* in the summer and by *Cyclotella sp.* in the winter. Phlips (2008) detected spatial differences, with bloom forming dinoflagellates in the north and south Forks and diatoms in the lower St. Lucie Estuary.

Chlorophyll *a* as an Environmental Indicator

Chlorophyll *a*, a measure of phytoplankton biomass, is often used as an indicator of estuarine condition, especially with regard to eutrophication (Bricker *et al*., 1999). In relatively deep systems, large phytoplankton blooms may lead to hypoxia or anoxia. In shallow systems blooms may increase light extinction to the point where benthic SAV can no longer survive

(Twilley *et al.*, 1985). It is this latter effect that makes chlorophyll *a* an attractive candidate for an environmental indicator in many coastal systems in Florida (e.g., Tampa Bay [Greening and Janicki, 2006]; Florida Bay [Boyer *et al*., 2009]). In such systems, increases in chlorophyll *a* can indicate a basic shift from a system where primary productivity is primarily benthic and detritus based, to one where productivity is pelagic and phytoplankton based (Boyer *et al*., 2009).

In shallow riverine estuaries, control of light attenuation can be shared between several water quality parameters. In many south Florida estuaries light attenuation in the upper brackish regions is controlled by colored dissolved organic matter (CDOM), which varies directly as a function of river discharge. It is not until dilution with seawater and other processes to reduce the CDOM concentration, that there is enough light for phytoplankton to bloom (McPherson *et al*., 1990). Ironically, it is only after phytoplankton themselves are released from light limitation that they can in turn affect benthic production through light limitation. Hence, the use and interpretation of chlorophyll *a* as an indicator of eutrophication or system status in river estuaries must account for the modulating effects of freshwater discharge (Doering *et al*., 2006). However, in the southern portion of the system (Florida Bay) light attenuation is overwhelmingly dominated by suspended sediments and phytoplankton blooms are rarely light-limited (Kelble *et al*., 2005).

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3.1.4 Periphyton-Water Quality Relationships

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Periphyton communities are valuable indicators of ecosystem status and change in the Everglades because of their ecological and biogeochemical importance, their sensitivity to human-induced changes in water quality, and their ubiquity across the ecosystem (McCormick and Stevenson, 1998; Gaiser, 2009). High periphyton biomass and productivity is characteristic of slough and wet prairie habitats throughout the oligotrophic managed Everglades (McCormick et al., 1998; Gaiser et al., 2006) and provide both food and habitat for invertebrates and small fish (Chick et al., 2008; Liston et al., 2008). Periphyton mats constitute a major sink for nutrients such as phosphorus (P) and, thus, regulate nutrient availability across oligotrophic portions of the ecosystem (McCormick et al., 1998; Noe et al., 2003; Gaiser et al., 2006). Predictable relationships between periphyton abundance, taxonomic composition and nutrient content and water quality have been identified and used to develop Restoration Coordination and Verification (RECOVER) indicators (Gaiser, 2009).

Relationships between periphyton and nutrient enrichment are well established for the Everglades (McCormick and O'Dell, 1996; McCormick et al., 1996; 1998; 2001; Pan et al., 2000; Gaiser et al., 2004; 2005). P is the principal limiting nutrient in the oligotrophic Everglades and even low level additions can result in significant changes in community structure and function. Secondary nitrogen (N) limitation may occur in P enriched portions of the Everglades (McCormick et al., 1996), but N exerts little control over periphyton at background P levels (Chiang et al., 2000). Oligotrophic communities exhibit a predictable series of responses to P enrichment, including rapid increases in periphyton P content followed by declines in biomass and cover and shifts in taxonomic composition. The most pronounced and visible response is the disintegration and disappearance of the thick floating, benthic, and epiphytic mats of cyanobacteria and diatoms that are characteristic of hard-water portions of the managed Everglades. These mat-forming communities are replaced by filamentous chlorophyte (green) algae in habitats exposed to low levels of P enrichment and by cyanobacterial-diatom mats dominated by eutrophic indicator taxa in the most highly enriched areas. These eutrophic communities typically exhibit lower biomass and less predictable coverage than do oligotrophic communities. Additionally, the trophic support value of eutrophic communities may be lower due to differences in physical structure. At the landscape scale, shifts in vascular plant communities in response to P enrichment, in particular the conversion of sloughs and wet prairies to dense mono-specific stands of cattail, reduces the coverage and productive capacity of periphyton in P-enriched areas of the Everglades (McCormick et al., 2009).

Periphyton P content has been proposed as an especially sensitive indicator of low-level P enrichment (Gaiser et al., 2004). Excess P delivered to oligotrophic areas is rapidly sequestered by P-limited periphyton mats and other microbiota. In controlled P-dosing experiments, periphyton P accumulated over time in response to enrichment in the absence of any detectable change in water-column P concentration. Similarly, elevated periphyton P concentrations were documented downstream of canal P inputs at locations where water-column concentrations remained at background levels. This temporal separation of periphyton and water-column enrichment differs from pelagic zones of lakes where water-column total phosphorus (TP) levels reflect both P supply and algal (phytoplankton) responses to enrichment.

Much of the initial information on periphyton responses to P enrichment was obtained from field studies conducted in Water Conservation Area 2A (WCA 2A) (Pan et al., 2000; McCormick et al., 2002). Systematic ecosystem-wide sampling has since been conducted to document the consistency of periphyton responses across P gradients in the different regions (hydrologic units) of the Everglades (Gaiser et al., 2006). Consistent taxonomic indicators of unenriched and enriched conditions were identified, but individual species exhibited regional differences in their P optima and tolerances. Similarly, periphyton P content was found to vary among oligotrophic reference areas largely as a function of the calcite content of the periphyton material. These findings illustrate the importance of calibrating periphyton metrics independently for different parts of the Everglades.

Concentrations of major ions (mineral chemistry) represent a second major chemistry gradient in the Everglades and the primary water quality factor distinguishing periphyton communities among oligotrophic areas in different regions. Mineral concentrations within the Everglades WCAs are determined by the relative importance of direct rainfall (low mineral content) and canal inflows (high mineral content) to the water budget (McCormick and Harvey accepted). The rainfall-fed interior of the Loxahatchee National Wildlife Refuge (WCA 1), for example, maintains a soft-water chemistry (specific conductance typically between 100-200 µS/cm) and supports a periphyton community that is taxonomically and functionally distinct from the calcareous community that dominates canal-influenced areas (specific conductance as high as 800-1000 µS/cm) such as WCA 2A (Swift and Nicholas, 1987; Gaiser et al., 2006). Available paleoecological evidence indicates that this soft-water condition and periphyton type was more widespread across the predrainage Everglades (Slate & Stevenson, 2000; Winkler et al., 2001). The soft-water periphyton community is sensitive to increases in water mineral content and declines rapidly in dominance as specific conductance increases above approximately 200 µS/cm (McCormick accepted), a level that is typically exceeded in areas that experience even small inputs of canal water.

Factors other than water chemistry exert significant influences on Everglades periphyton communities. Periphyton abundance and taxonomic composition exhibit seasonal patterns (McCormick et al., 1998) that are driven not only by changes in temperature and solar radiation but by hydrologic drivers such as water depth and water delivery rates (Iwaniec, 2006). Hydroperiod exerts a strong influence on periphyton taxonomic composition and function, with short hydroperiod sites favoring increased dominance of calcareous cyanobacteria and associated mat calcite content and a diminished diatom and chlorophyte algal component (Gottlieb et al., 2006). These other environmental influences must be considered when interpreting local periphyton conditions in a water-quality context.

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3.1.5 Mercury in the Everglades: The South Florida Mercury Bioaccumulation Module and the Mercury Monitoring and Assessment Program

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South Florida Mercury Bioaccumulation Module

The overarching goal of the South Florida Mercury Bioaccumulation Module (as part of the Monitoring and Assessment Plan [MAP] from 2004-2006) under Restoration, Coordination and Verification (RECOVER) was to monitor mercury bioaccumulation to ensure that the Comprehensive Everglades Restoration Plan (CERP) does not inadvertently worsen the existing mercury problem in south Florida to the point that risks to humans or wildlife outweigh restoration benefits (MAP, 2004). Many water bodies in south Florida are under fish consumption advisories to protect human health due to mercury contamination, including the Everglades and Florida Bay. Under the MAP module three ecological premises are established to achieve this goal and to develop a direction for monitoring and research. The premises are as follows:

(1) constructed wetlands, especially newly flooded wetlands, can be a significant source of both inorganic and more importantly, organic mercury, (2) the efficiency of sulfate-reducing bacteria to methylate inorganic mercury is optimized under specific sulfide-to-sulfate ratios that typically occur when the average surface water concentration of sulfate is greater than one milligram per liter (1 mg/L) and less than 20 mg/L (3) drying and re-wetting of certain hydric soils can affect mercury biogeochemistry in sediment and (4) discharge of aquifer storage and recovery (ASR) water containing elevated sulfur into surface waters and the potential for enhanced methylation in the receiving water.

Under the MAP program the first step in assessing these premises is to evaluate potential mercury bioaccumulation pathways to humans (via analysis of edible fish fillet) and wildlife (via analysis of whole fish) using appropriate target species. To develop exposure pathways to humans, establishment of baseline data /reference conditions are needed to evaluate potential detrimental increases. There were two components set forth by the RECOVER program to develop a baseline database: (1) surveying the literature and gathering information from agencies known to have measured mercury in fish in south Florida, and (2) filling the gaps by performing additional fish collections. For baseline data collection, the RECOVER program contracted the National Oceanic and Atmospheric Administration (NOAA) under the direction of Dr. David Evans (Principal Investigator). Until 2009, data has been obtained from six agencies and programs (NOAA, Florida Bay Studies, NOAA-South Florida Water Management District [SFWMD] Florida Bay Studies, Fish Wildlife Research Institute [FWRI] Fishery Independent Monitoring Program, Florida Fish and Wildlife Conservation Commission [FWC] Freshwater Monitoring Program, Florida Department of Environmental Protection [FDEP] Marine Monitoring Studies and U.S. Environmental Protection Agency [EPA] Gulf of Mexico Program). These agencies had data beginning in 1989 for various fish species; however, there were significant differences among the databases and, overall, the total number of fish obtained from these agencies was determined to be too low. Therefore, to contribute to baseline collections, NOAA collected an additional 3,387 fish from 23 inland and coastal stations throughout south Florida covering six species (largemouth bass, bluegill, crevalle jack, gray snapper, snook and spotted seatrout). These collections occurred from 2006 to 2008. The following section provides a brief synopsis of these data and analysis results.

Synopsis of Monitoring and Assessment Plan Baseline Data Results: 2006 to 2008

For the 2006-2008 data collected by NOAA variability in mercury concentrations was high among all species with coefficients of variation ranging from 25 to 96 percent. Among the freshwater regions, Big Cypress National Preserve and Everglades National Park demonstrated the highest observed concentrations of mercury in sentinel fish (***Table 3-1***). Among the coastal marine regions, the contiguous regions at the sound end of Florida, Biscayne Bay, Card and Barnes Sounds and Florida Bay exhibit the highest mercury concentrations in sentinel fish. These coastal regions are of limited freshwater input and flushing which likely promotes high methylation rates and bioaccumulation. A MAP bioaccumulation performance measure has been defined as, "no statistically significant (90 percent confidence level) increase in levels of mercury bioaccumulation in tissue of fish…" (Evans, 2008). The appropriate analysis has not yet been run to help determine trends in the collected NOAA data to evaluate this performance measure; however, for the data collected there was little difference in mercury concentration between 2006 and 2008. A separate comparison analysis showed that mercury concentrations do not vary due to sex of the fish; however, region, year and total length contributed to significant variability in mercury concentration for all species (Evans, 2006; 2008).

South Florida Water Management District Mercury Monitoring and Assessment Program

The SFWMD Mercury Monitoring and Assessment Program was established after there was an identified need to develop working knowledge of mercury transfer and bioaccumulation within stormwater treatment areas (STAs). Currently, this program has two roles (1) compliance-related monitoring and (2) contributions to research to understand mercury's fate and transport. Part of the compliance monitoring plan is to evaluate mercury transfer and bioaccumulation for CERP projects using the CERP guidance memorandum (CGM) 42. The CGM 42 applies a phased, tiered approach to monitor and evaluate mercury concentrations in soil, surface water, fish species including the internal processing and downstream delivery of mercury from operating units (i.e., STAs, reservoirs). The CGM 42 has only been in use for three years thus making it difficult to assess how CERP projects are performing from a mercury transport and bioaccumulation perspective as measurable changes can take several years to detect.

Elevated levels of mercury in biota from Everglades National Park were first reported by Ogden (1974). In 1988, reports of mercury levels in largemouth bass (*Micropterus salmoides*) in the Water Conservation Areas (WCAs) exceeding 1 mg/L prompted more widespread sampling of both fish and wildlife. As a result of further sampling, Ware et al. (1990) reported elevated mercury levels in alligators (*Alligator mississippiensis*), crayfish (*Procambarus fallax*), softshell turtles (*Apalone ferox*), pig frogs (*Rana grylio*), mottled ducks (*Anas fulvigula*), white-tailed deer (*Odocoileus virginianus*), and the endangered Florida panther (*Felis concolor*). Mercury continues to be a chronic water quality problem in the Everglades Protection Area, impacting humans and fish-eating wildlife because of excessive bioaccumulation of mercury in fish. High concentrations of mercury in fish have not only been documented in the freshwater reaches of the Everglades Protected Area (Loftus et al., 1998; Axelrad et al., 2009), but also downstream in Florida Bay (Strom and Graves, 2001; Evans et al., 2003) and the Gulf of Mexico (Adams et al., 2003; Axelrad et al., 2009).

Outside of compliance–related monitoring, several discoveries have been made with respect to mercury methylation over the last ten years. In south Florida, factors that promote mercury methylation or bioaccumulation include sulfate loading, high intensity rainfall, and the largely organic soils/sediments (Gilmour et al., 1998; 2004; Guentzel et al., 1995; 2001; Dvonch et al., 1998; Cai et al., 1999; Benoit et al., 2001; Scheidt and Kalla, 2007: Liu et al., 2008). Studies conducted by Gilmour et al. (2004) under the Aquatic Mercury Cycling in the Everglades (ACME) study detail mechanisms that control methylation (e.g., sulfur "break point"). Also shown by this study is the species of reduced sulfur in soil plays an important part in methylation efficiency. Specifically, despite being the smallest fraction of total sulfur in soils, acid volatile sulfides (AVS) can be readily oxidized in surface soils and are thus available as electron acceptors for mercury methylation. Since the late 1990s levels of methyl mercury in biota (e.g., fish, wading birds) have declined in central WCA-3. This decline has been attributed to a decrease in local mercury emissions in south Florida (Atkeson et al., 2005). There is increasing evidence which demonstrates mercury sourced to the Everglades from atmospheric deposition is now predominantly from global rather than local (within Florida) sources (Atkeson et al., 2005; Axelrad et al., 2007; 2008). In all, documented studies have shown mercury methylation in south Florida is a complex function of converging (1) hydrology, (2) biogeochemistry, and (3) atmospheric processes and mercury methylation and bioaccumulation can be highly disjointed biogeochemical processes.

TABLE 3-1: TWO-YEAR MEAN MERCURY CONCENTRATIONS OF MERCURY (PPM WET WEIGHT) IN SENTINEL FISH BY REGION

Region	Largemouth Bass	Bluegill	Crevalle Jack	Gray Snapper	Snook	Spotted Seatrout
Big Cypress Preserve	.833	.521				
C-44 Canal	.264	.109				
Caloosahatchee River	.362	.151				
Everglades National Park (ENP)	.613	.267				
Grassy Waters Preserve	.559	.170				
Kissimmee River	.461	.176				
Lake Okeechobee	.240	.079				
Loxahatchee River	.457	.149				
Model Lands	.570	.254				

WCA2B/3B	.455	.235				
Biscayne Bay			.755	.168		
Card & Barnes Sounds			.806	.255		
Florida Bay			.815	.246		
ICW Indian River Lagoon			.519	.133		
ICW Southeast			.478	.204		
Loxahatchee Estuary			.430	.124		
San Carlos Bay			.594	.158		
Southwest Coast			.592	.149		
Southwest ENP north			.527	.153	.346	
Southwest ENP south			.561	.154	.490	
St. Lucie Estuary			.450	.110	.200	
Ten Thousand Islands			.527	.229		
Whitewater Bay				.230		.546

Note: (adapted from Evans, 2008)

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3.1.6 Sulfur in the Everglades

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Summary
Sulfur is a major concern for Everglades restoration due to the high loading to the ecosystem, the large area of the ecosystem enriched with sulfate, and the myriad impacts of sulfur. Most of the sulfur loading originates within the Everglades Agricultural Area (EAA) and is evident as sulfate in EAA canal water. Various lines of geochemical evidence and sulfur mass balance are consistent with EAA soil oxidation (the EAA is pumped dry to allow crop production; IFAS, 2007), and agricultural use of sulfur in the EAA as the principal sources of the sulfate in EAA canal water. Sulfate from the EAA drainage canals penetrates deep into the Everglades Water Conservation Areas (WCAs), and may extend into Everglades National Park (ENP). Current plans to restore sheet flow and to deliver more water to the Everglades may increase overall sulfur loads to the ecosystem, and move sulfate-enriched water further south.

Sulfate loading to the Everglades increases microbial sulfate reduction (MSR) in soils, leading to depressed redox conditions, enhanced cycling of nutrients in soils, production of toxic sulfide, and high production and bioaccumulation of neurotoxic methylmercury (MeHg) that may threaten wildlife..A comprehensive Everglades restoration strategy should include reduction of sulfur loads as a goal because of the many detrimental impacts of sulfur on the ecosystem. Monitoring data show that the ecosystem response to changes in sulfate levels is rapid, and strategies for reducing sulfate loading may be effective in the near-term. A multi-faceted approach employing best management practices for sulfur in agriculture, agricultural practices that minimize soil oxidation, and changes to stormwater treatment areas (STAs) that increase sulfate retention could help achieve reduced sulfate loads to the Everglades, with resulting benefits.

Introduction
The south Florida wetlands ecosystem (greater Everglades) is a large and diverse wetland environment interconnected by the flow of fresh water from one part of the ecosystem to another, and providing a habitat for an abundance of wildlife (Davis and Ogden, 1994). This ecosystem is impacted by the combined effects of urbanization, agriculture, and nearly 100 years of water management entailing construction of ***canals***, levees, and impoundments. Water quality is one key issue facing restoration of the ecosystem (Light and Dineen, 1994; Sklar et al., 2002). Water quality in the Everglades has historically focused on phosphorus contamination from sources in the EAA (Koch and Reddy, 1992; Davis, 1994). Phosphorus contamination, however, is not the only water quality issue of concern in the Everglades (Bates et al., 2002; Pfeuffer and Rand, 2004; Scheidt and Kalla, 2007). Sulfur has emerged as another critical water quality issue (Orem, 2004).

Sulfur Distribution
Sulfur enters the Everglades primarily as highly water-soluble sulfate. Most freshwater wetlands have low levels of sulfate (Wetzel, 1975; Gorham et al., 1985), and unenriched areas of the Everglades have very low sulfate levels, ranging from 1 to less than 0.1 mg l^{-1} (Gilmour et al.,

2007b; Scheidt and Kalla, 2007). Parts of the northern Everglades, however, have average sulfate levels of 60 mg l^{-1}, far in excess of background levels and 1,000 times more than levels of phosphorus entering the ecosystem (Gilmour et al., 2007b; Payne et al., 2009). Approximately 60 percent of the Everglades have surface water sulfate concentrations above 1 mg l^{-1}. Across the freshwater Everglades the highest average surface water sulfate concentrations are found in canal water in (and just downstream of) the EAA. At interior marshes within the WCAs, there is an overall gradient in sulfate concentration from north to south. Elevated sulfate concentrations occur near major canals throughout the ecosystem, even in areas to the south such as along the L-67 Canal in southern WCA 3A and where the L-67 terminates in ENP. Surface water sulfate concentrations across the Everglades tend to be highest during the wet season due to the pumping of stormwater from the EAA into the Everglades for flood control (Scheidt et al., 2000; Scheidt and Kalla, 2007). Compared to phosphorus, sulfate penetrates much farther into the marsh from STAs and canal discharge points. Sulfur is a plant nutrient required at approximately the same levels as phosphorus (Hawkesford and DeKok, 2007), but is discharged into the Everglades at 1,000 times the levels for phosphate.

Sources of Sulfur

Potential sulfur sources in the watershed are many, but geochemical data and a preliminary sulfur mass balance for the EAA (Gabriel et al., 2010) are consistent with sulfur currently used in agricultural, and sulfur released by oxidation of organic EAA soils (including legacy agricultural applications, and natural sulfur) as the primary sources of sulfate enrichment in the EAA canals. Canals within the EAA have the highest surface water sulfate concentrations in the greater Everglades region (Scheidt et al., 2000; Bates et al., 2001 and 2002; Chen et al. 2006; Gilmour et al., 2007b). Everglades marshes with the highest sulfate levels are located near points of canal discharge. In general, sulfate concentrations decrease with distance from the EAA, both to the north and south. Thus, surface water sulfate distributions suggest that a major source of sulfate exists within the EAA, and that canal water is the principal conduit delivering sulfate to the Everglades. Rainfall and dryfall have sulfate concentrations that are too low to account for the high levels of sulfate in EAA canals (Bates et al., 2002; McCormick and Harvey, 2010). Groundwater may have high sulfate concentrations and could be a potential source of sulfate to canals (Bates et al., 2002), but several lines of geochemical evidence indicate that groundwater is not an important source of sulfate to surface water in canals or marsh areas (Axelrad et al., 2008 and 2009). Extensive use of sulfur in agriculture in the EAA (Bottcher and Izuno, 1994) suggests that much of the sulfate in EAA canals may originate from agricultural application. (Bates et al., 2002). Elemental sulfur (S^0) is used as a soil amendment and fungicide in the EAA (Bottcher and Izuno, 1994). Sulfur isotopic analyses ($\delta^{34}S$) of S^0 used in the EAA (Bates et al., 2001 and 2002) had a range of values (15-20‰) consistent with the isotopic composition ($\delta^{34}S$) of sulfate in EAA canal water. Sulfate extracted from the upper 10 centimeters of soil in an active sugarcane field in the EAA had a $\delta^{34}S$ value of 15.6 ‰ (Bates et al., 2002), consistent with that of agricultural S^0. Overall, it appears that much or most of the sulfate present in canals originates from the EAA lands, with an additional modest net input of sulfate to canals from Lake Okeechobee inflow. The broad use of sulfur in agriculture (current and legacy in soil), and the elimination of other sulfur sources (groundwater, wet/dry deposition) to canals suggests that soil oxidation and current sulfur use in the EAA account for the major proportion of the sulfate load to the Everglades.

Impacts of Sulfur

The excess sulfate entering the Everglades has fundamentally changed its biogeochemistry through stimulation of microbial sulfate reduction. The microbial community structure in soils over wide areas has been altered from one dominated by methanogenesis to one dominated by microbial sulfate reduction. Impacts of increased sulfate loads may include: (1) stimulation of MeHg production, (2) buildup of sulfide to levels that may be toxic to flora and fauna, (3) enhanced release of nutrients from organic soils, (4) changes in soil redox conditions, and (5) changes in metal speciation through formation of insoluble metal sulfides.

Probably the most important impact of sulfur on the ecosystem is as a major control on the production and bioaccumulation of MeHg. MeHg is a major environmental issue for piscivorous wildlife in the Everglades, and for human health from consumption of MeHg-contaminated Everglades fish (Axelrad et al., 2007 and 2008). Florida has issued a fish consumption advisory for all of the Everglades (Florida Department of Health, 2003), and MeHg levels in top predator fish in ENP are among the highest levels in the nation for freshwater fish (Axelrad et al., 2009; Rumbold et al., 2008). Sulfate is known to be an important control on the production of MeHg in aquatic ecosystems (Gilmour et al., 1992; Benoit et al., 2003), including the Everglades (Gilmour et al. 1998). Field observations, laboratory experiments, and mesocosm studies have shown positive correlations between net MeHg production and surface water sulfate concentrations across the Everglades over the range of 0.5 to 20 mg l^{-1} sulfate (Gilmour et al., 2007a; Scheidt and Kalla, 2007). However, at pore water sulfide concentrations greater than 1 mg l^{-1} the buildup of sulfide becomes inhibitory to MeHg production, and the positive correlation between sulfate and MeHg breaks down.

Since the late 1990s levels of MeHg in biota (fish, and wading birds) have declined in central WCA 3A, and this decline has been attributed to a decrease in local Hg emissions in south Florida (Atkeson et al., 2005). However, deposition of total Hg on the central Everglades has stayed relatively constant over the past 15 years (Axelrad et al., 2008), suggesting that local emissions are not the major control on Hg deposition on the Everglades. Sulfate (and sulfide) levels in central WCA 3A also dropped from the late 1990s to present, as discussed earlier. Thus, a decline in sulfate loading appears to be the biggest control on declines in MeHg production and bioaccumulation in central WCA 3A over the past decade (Gilmour et al., 2007a; Axelrad et al., 2008).

Management of Sulfur for Restoration

Restoration of the Everglades to a condition approximating its pre-development state by reestablishing natural sheet flow of water, and moving more water to areas (mostly in the south) that currently lack sufficient water would require using water originating in Lake Okeechobee and passing through the EAA. This water is contaminated with a number of chemicals harmful to the ecosystem, including sulfate. Sulfate is a particular concern because of its high concentration and many adverse impacts. Resource managers should recognize that there may be unintended adverse ecological impacts as a result of actions taken to improve water distribution without addressing all of the important water quality issues.

Research findings suggest that past and present EAA agricultural practices introduce much of the sulfate entering EAA canals, and that a reduction in sulfate loading would yield significant environmental benefits to the Everglades. Reductions in the amount of sulfur currently used in EAA agriculture could be achieved via implementation of best management practices (BMPs), balancing agricultural needs with minimizing sulfate runoff. However, even if BMPs on sulfur use in the EAA are successful, significant sulfate loading would likely continue from EAA soil oxidation and sulfate inputs from Lake Okeechobee. Mitigation strategies would be needed to further reduce sulfate loading to the ecosystem. Various mitigation approaches are summarized elsewhere (Orem, 2007). Modification of existing STAs for more effective sulfate removal is especially appealing.

Although reduction of sulfate runoff to the Comprehensive Everglades Restoration Plan (CERP) performance measure of 1 mg l^{-1} is desirable, it should be noted that any reduction in overall sulfate loads would benefit the Everglades. The variety and magnitude of sulfur sources would make attaining the CERP goal for sulfate a challenge. Nevertheless, studies have demonstrated that any significant reduction in current sulfate loads to the Everglades would have beneficial results in the near term, especially with regard to levels of MeHg. Considering that most of the mercury deposited on the Everglades appears to originate from distant sources (outside the reach of State and Federal regulators), reductions in sulfate loading to the Everglades may represent the most viable approach for reducing MeHg production and bioaccumulation within an ecosystem that has some of the highest levels of MeHg in biota of any wetland in the USA. The success of BMPs and mitigation strategies using STAs for reducing phosphate loads to the Everglades suggests that similar approaches for sulfate reduction may be effective.

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3.1.7 Copper in the Everglades: Contamination in Florida Apple Snails (*Pomacea paludosa*)

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Citrus groves have been proposed for use in Everglades restoration projects as stormwater treatment areas (STAs) and water storage reservoirs. Copper is a common fungicide used in cultivation of citrus and has been found to accumulate in soils (McCoy et al., 2009). Upon inundation, copper in the soils will be released and available for uptake in the aquatic food web. The ability of molluscs to uptake copper is well documented in the literature and is of potential concern for molluscan predators, such as the federally endangered Everglade snail kite (*Rostrhamus sociabilis plumbeus*).

A 2003 ecological risk assessment on the proposed conversion of a citrus grove into a water reservoir as part of an Everglades restoration project predicted that copper-impacted soils might adversely impact the Everglade snail kite (URS, 2003). The source of risk was through the bioaccumulation of copper in the Everglade snail kite's diet, which is almost exclusively the Florida apple snail (*Pomacea paludosa*). The findings of this risk assessment lead to negotiations between the U.S. Fish and Wildlife Service and the South Florida Water Management District that resulted in a recommended interim soil screening level of 85 mg/kg copper for protection of the Everglade snail kite at all sites to be inundated for Everglades restoration projects. This proposed screening level was in addition to the sediment quality assessment guidelines issued by the Florida Department of Environmental Protection (threshold effect concentration [TEC] [32 mg/kg]; probable effect concentration [PEC] [150 mg/kg]) for protection of sediment-dwelling organisms (MacDonald et al., 2003). Soils that exceed 85 mg/kg of copper are recommended to undergo some form of remedial action, specifically soil inversion, removal, or capping prior to use as a water resource project.

Since 2003, several studies have been conducted to better understand the uptake and toxicity of copper in Florida apple snails. Rogevich et al. (2008) showed acute toxicity of dissolved copper to juvenile Florida apple snails (96-h LC50 for 2-30 day old snails ranged from 34 to 45 µg/L). Reproductive effects, including significantly reduced clutch production (8-16 µg/L) and egg hatching (16 µg/L), have also been demonstrated (Rogevich et al. 2009). These concentrations of dissolved copper, which resulted in acute toxicity and reproductive effects, are similar to, or lower than some concentrations that have been shown to desorb from former agricultural lands acquired for Everglades restoration projects. Hoang, et al. (2008b) observed concentrations ranging from 9.1 to 308.2 µg/L in overlying water from static incubation of affected soils and clean water (1:2 soil:water). These experimental conditions may represent situations during dry periods when STAs may dry down, resulting in minimum water depths overlying affected soils. Copper concentrations in overlying water are lower (3.8 to 25 µg/L) when a larger volume of water (Hoang, et al 2008b, NewFields 2009) and/or occasional water replacement are used (NewFields 2009), which may better represent conditions of low flow (i.e., not static) in STAs and water resource reservoirs.

Repeated flooding events, which are likely to occur in the operation of Everglades restoration projects, are not expected to greatly decrease the concentration of copper desorbing from soils into the surface water (Hoang et al., 2009; NewFields 2009). In fact, the concentration of free copper (Cu+2), which is highly bio-available, was shown to increase, due to the decrease in the dissolved organic carbon (DOC) that occurs with repeated flooding events; however, there was no significant correlation between the amount of Cu+2 and the soil copper concentration ($p = 0.36$, Pearson correlation) (Hoang et al., 2009).

Uptake of copper through sediments and diet has also been demonstrated, with uptake from the latter being the primary exposure route for the Florida apple snail (Frakes et al., 2008; Hoang et al., 2008a). Laboratory studies have demonstrated higher mortality and whole body copper concentrations in the Florida apple snails exposed to flooded copper-enriched soils as compared to Florida apple snails exposed to water alone (Hoang et al. 2008a; Hoang and Rand, 2009). When a dietary route of copper exposure was provided, bioaccumulation factors (BAFs), the ratio of the concentration of copper in the Florida apple snail tissue to the concentration of copper in the environment, were three to eight times higher (ranging from <1 to 10) than exposure through sediments (soil and/or dermal contact) (Hoang et al., 2008a). A field study by Frakes et al. (2008) found BAFs ranging from 6 to 30 in Florida apple snails collected from various wetlands in close proximity to citrus groves and a reference location (Figure ***3-1***). Preliminary results from a copper exposure microcosm study, which likely simulates the upper end of exposure for Everglade snail kites, are also producing similar BAFs (ranging from 15 to 37) (G. Rand, pers. comm., 2010). For comparison, a BAF of 5.6 was used to calculate the 85 mg/kg recommended interim screening level for copper. Based on results that include copper exposure through a natural dietary component, the 85 mg/kg interim screening level may not be conservative enough for the protection of the Everglade snail kite. However, factors affecting exposure of Florida apple snails, and Everglade snail kites to copper in future STAs are complex, and it is unknown whether long-term average exposure to Everglade snail kites is accurately represented by the currently available experimental data.

The ability of Florida apple snails to bioaccumulate copper has implications for the successful survival and recruitment of the Florida apple snail and its predator the Everglade snail kite at STAs and water reservoirs created for Everglades restoration projects; however, there is still uncertainty in the amount of copper that is actually bio-available to the Everglade snail kite. It is unclear whether apple snails have a mechanism of sequestering copper that makes it partly unavailable for trophic transfer to predators. Additional information on Florida apple snail bioaccumulation of copper, copper bio-availability, and exposure patterns of Everglade snail kites under various environmental conditions may be necessary to identify appropriate risk management scenarios for Everglades restoration projects.

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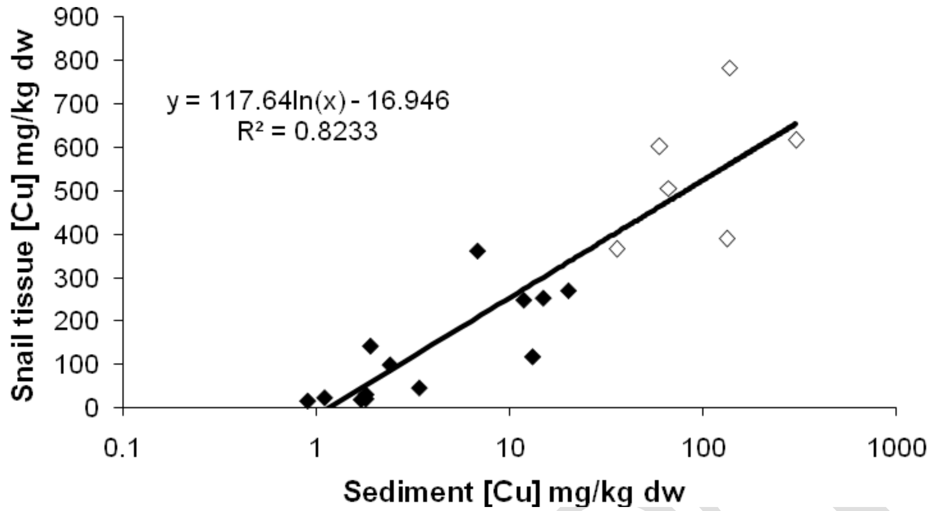

Key:

solid diamonds represent Florida apple snails
open diamonds represent viviperidae snails

FIGURE 3-1: SCATTER PLOT OF INDIVIDUAL SUBSITE COPPER CONCENTRATIONS IN SNAILS AND SEDIMENTS COLLECTED FROM FIVE LOCATIONS IN SOUTH FLORIDA

3.1.8 Other Contaminants in the Everglades

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The Final Integrated Feasibility Report and Programmatic Environmental Impact Statement,published in April 1999, has numerous discussions concerning contaminants, primarily pesticides and metals, and their potential impacts to the Everglades restoration. The 2004 Monitoring and Assessment Plan (MAP) had numerous modules with discussions and suggested monitoring for contaminants. However, by 2008, module discussions on contaminants were not present. The 2008 Draft MAP noted that the monitoring costs are perceived to be prohibitively high and have not contributed to informing management decisions. Also, the 2007 System Status Report (SSR) and draft 2009 SSR did not contain any discussion of contaminants or monitoring projects. Therefore, the discussion of "knowledge gained" will have to rely on "new scientific knowledge", relevant to restoration.

Stormwater Treatment Area Permit Monitoring (SFWMD, 2004)
Pesticide sampling had been performed for each of the stormwater treatment areas (STAs) on a quarterly basis, starting with the issuance of respective permits. An evaluation of concentrations of the routinely detected pesticides (atrazine and ametryn) determined the outflow concentration for both compounds was greater than the inflow concentration at most of the STAs, but only the ametryn values at the outflow of STA-5 exhibited statistical significance. STAs did not completely degrade the detected compounds.

Ambient Pesticide Monitoring Program: 1992 to 2007 (Pfeuffer, 2009)
The South Florida Water Management District (SFWMD) has maintained a mandated pesticide monitoring program in south Florida since 1984. The monitoring provides data to determine the condition or changes in the quality of water being delivered to Lake Okeechobee, Everglades National Park, the Water Conservation Areas (WCAs), and Florida Bay.

For contaminant monitoring, the level of detection is critical for data evaluation. As identified for the insecticides ethion and diazinon, the concentrations at which a pesticide is of concern can be very low. Additionally, lower detection limits also reduces the chance of false negatives.

Atrazine and its associated degradation products (atrazine desethyl and atrazine desisopropyl) were the most frequently detected compounds in the surface water while DDE-p,p' (the degradation product of DDT) was most frequently detected in the sediment.

Atrazine was detected at all locations at least once. The top nine locations for detections or those where over 90 percent of the samples contained atrazine, were locations receiving drainage from either the Everglades Agricultural Area or urban areas. However, none of the detected concentrations were at a level of concern as they did not exceed the draft ambient aquatic life water quality criterion (USEPA, 2003) or the calculated acute or chronic toxicity values. Nine of the 14 locations selected for evaluation demonstrated a decreasing concentration over time for this reporting period.

The DDE-p,p’ residues were ubiquitous and the majority of sampling locations had concentrations that could have harmful effects on freshwater sediment-dwelling organisms. Of the 32 locations evaluated, only eight had average location concentrations that were less than the threshold effect concentration (TEC) (i.e., the value at which sediment concentration should not have a harmful effect on sediment-dwelling organisms) (MacDonald Environmental Sciences Ltd. and United Geological Survey, 2003). The average concentration at structures S6, S2, S5A, and S178 was higher than the probable effect concentration (PEC), which means that harmful effects to sediment-dwelling organisms are likely to be frequently or always observed. Trend analyses for these structures, as well as S177 and S3, demonstrated increasing concentration at S2 and S3, while decreasing trends were demonstrated at S178 and S177. Although lawful uses of DDT in the United States were curtailed by the U.S. Environmental Protection Agency (USEPA) in the early 1970s (USEPA, 1990), the persistence of its predominant environmental metabolite DDE-p,p’, has resulted in residue concentrations that are still at a potentially harmful level.

To determine exceedances of sediment or water quality criteria, pesticide concentrations from grab samples are typically compared to numerical standards or guidelines for sediment or water. However, specific criteria are lacking for most of the pesticides. Calculated criteria are based on the lowest acute toxicity value from the most sensitive aquatic species tested in a short-term test. However, these values are often from species that are not native to south Florida ecosystems. In general, aquatic databases are limited for native species.

Additionally, pesticide detections frequently occur with more than one compound at a time. When evaluated on a single compound to a single species criterion, a discernable impact is not always evident. However, if the same family of compounds is detected, a synergistic or cumulative impact may be occurring. Using a multiple substance risk approach, based on a concentration addition model, Schuler and Rand (2006) identified a high risk to plant and algal communities from the herbicide mixtures detected at selected locations by SFWMD. The species sensitivity distributions could be used to characterize acute and chronic effects and the susceptibility of organisms to different chemical stressors. This approach determines what fraction of species is expected to be potentially affected above its acute or chronic effect level at a given environmental concentration.

Everglades Protection Area Project: 1994 to 2009

One of the requirements of the Settlement Agreement is the annual sampling of sediment for pesticides and metals at two sites, within each WCA. The most frequently detected pesticide was DDE-p,p’. All of the concentrations exceeded the TEC. The majority of detected concentrations at the north central sampling location in WCA 1 (LOX8) exceeded the PEC.

Using the interpretive tool for assessing metal enrichment in freshwater sediments (FDEP 2002) resulted in several of the metals concentrations being greater than background levels or enriched (***Table 3-2***).

TABLE 3-2: PERCENTAGE OF METAL EXCEEDANCES OF BACKGROUND COMPARISON LEVELS AT WATER CONSERVATION AREA MONITORING SITES

	Monitoring Sites					
	LOX8	LOX10	WCA2F1	CA215	CA33	CA315
Arsenic	33	25	100	100	17	100
Cadmium	10	10	10	10	0	0
Chromium	8	17	17	17	0	0
Copper	100	100	82	82	36	91
Lead	100	100	83	92	50	92
Mercury	100	100	100	100	100	100
Nickel	83	92	83	83	0	92
Silver	27	30	18	33	0	25
Zinc	92	67	69	50	0	92

However, comparing average metal concentrations to the TEC identified that the arsenic, lead, and mercury concentrations were greater than the respective guideline at CA315. Additionally, average mercury values exceeded the TEC guideline at LOX8 and LOX10.

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3.2 Technologies to Achieve Water Quality

The following topic summaries are under the heading "3.2 Technologies to Achieve Water Quality":

- 3.2.1 Structural Technologies: Stormwater Treatment Areas
- 3.2.2 Non-structural Methods: Best Management Practices

3.2.1 Structural Technologies: Stormwater Treatment Areas

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Contributing reviewers: Laurel Larsen (USGS), Matt Harwell (USFWS), Dan Scheidt (USEPA), Anonymous reviewer (USACE), Ed Brown (USACE), Chad Kennedy (FDEP)

Design of Stormwater Treatment Areas: Long-Term Plan Enhancements
As required by the 2003 amendments to the Everglades Forever Act (EFA), the South Florida Water Management District (SFWMD) is implementing the Long-Term Plan for Achieving Everglades Water Quality Goals (Long-Term Plan) in order to achieve the phosphorus (P) criterion in the Everglades Protection Area (EPA). The Long-Term Plan was developed using the results of the Advanced Treatment Technology (ATT) and Stormwater Treatment Area (STA) Optimization research program conducted between 1995 and 2003 in which treatment technologies with potential to achieve very low total phosphorus (TP) concentrations were investigated. The original design of the STAs relied on emergent vegetation throughout the treatment cells but, based on the ATT research, the Long-Term Plan relies upon a combination of emergent aquatic vegetation (EAV) and submerged aquatic vegetation (SAV) (***Figure 3-2***). Thousands of acres of STA cells were converted to SAV pursuant to the recommendations in the Long-Term Plan. Dye tracer tests conducted in two of the SAV cells depicted remarkably efficient hydraulic characteristics in one and relatively efficient hydraulic characteristics in the other (DB Environmental, 2004; DB Environmental, 2005). Periphyton-based Stormwater Treatment Area (PSTA) biological treatment which is currently being studied by the SFWMD (See STA Chapters of 2005 through 2010 SFER) and the (Jones, 2008; Shepp, 2009) may provide additional treatment capability at the end of the EAV/SAV treatment train. Evaluation of the PSTA treatment technology including the SFWMD's and USACE's research data is underway to determine the potential further implementation of PSTA.

Design of Stormwater Treatment Areas: Treatment Cell Topography
Constructing STAs with correct treatment cell topography is critical for achieving optimal STA performance (Kadlec and Wallace, 2009 pg. 795) especially those with very low target outflow P concentrations (Kadlec, 2000; DBEL, 2003). Highly uneven topography in STAs results in non-uniform flow, hydraulic short-circuiting and the inability to maintain target depths for the intended vegetation type (SFER, 2007, pg 5-123; SFER, 2008, pg 5-8; SFER, 2010, pg 5-93). Recent STA designs have specified grading of high areas to minimize potential for dry-out and filling of low areas such as remnant farm ditches parallel to flow to minimize short-circuiting.

Operation of Stormwater Treatment Areas: Wildlife Usage
The STAs have attracted large numbers of wildlife including but not limited to alligators and birds. An unintended consequence of the creation of such optimal wildlife habitat in the STAs has been nesting by birds protected under the Migratory Bird Treaty Act of 1918 (MBTA). The SFWMD worked closely with the U.S. Fish and Wildlife Service (USFWS) to develop the nation's first Avian Protection Plan (APP) for an STA (Pandion Systems, Inc., 2008). The focus of this APP is black-necked stilts (*Himantopus mexicanus*) and burrowing owls (*Athene cunicularia*). The APP is intended to minimize impacts to migratory birds nesting in the STAs while acknowledging that the STAs are operated for water quality treatment and flood control purposes. The plan provides an avian risk assessment methodology, mortality reduction

measures, and reporting protocols. Successful implementation of the APP has occurred over the past several years; nesting surveys are conducted through the nesting season and survey results are used in operations meetings to avoid or minimize impacts to migratory bird nests (Chimney, 2007; Chimney, 2008; SFER, 2010 pg 5-69). Other wildlife issues, including the Everglade Snail Kite nesting in the STAs, are coordinated closely with USFWS.

Design and Operation of Stormwater Treatment Areas: Extreme Weather - Hurricanes and Droughts

During 2004 and 2005, several tropical storms and hurricanes passed directly over the STAs. The wind and wave action associated with these extreme storms had in some cases very significant impacts on the STAs, particularly in the SAV cells, resulting in lengthy post-storm recovery periods for vegetative re-establishment and treatment performance recovery (SFER, 2006, pg 4-5). In some treatment cells where the storm damage was most severe, the SFWMD implemented major rehabilitation activities including sediment stabilization (rice planting) and SAV inoculation to help jump-start SAV re-growth. One of the lessons-learned from the hurricanes was the need to have backup power facilities at all major water control structures to allow operation when the power is out for an extended period of time (SFER, 2007, pg 5-4). For this reason, the SFWMD installed generator receptacles at all major STA structures that did not already have full generator backup systems. Also as a result of the hurricane impacts, the SFWMD began adding emergent vegetation strips in SAV cells to help reduce the effect of wind and wave action during large storm events (SFER, 2007, pg 5-4). At about the time the SAV cells appeared to be recovering from the storm damage, a multi-year regional drought impacted the STAs (SFER, 2008; SFER, 2009). Although avoiding dry-out has always been a directive for STA management, the severe regional drought conditions have meant that supplemental water from Lake Okeechobee has not always been available for delivery to the STAs. In 2008, the SFWMD developed a Drought Contingency Strategy to minimize negative impacts to the STAs during droughts (SFER, 2009). Despite implementation of the Drought Contingency Strategy's proactive measures to maintain minimum water levels in the treatment cells, many cells had extended dry-out periods during the recent record droughts that caused vegetation stress and impacts to treatment performance. Dry-out is a major concern because the rate of soil mineralization greatly increases and consequently results in spikes in P concentration upon rehydration (SFER, 2010). Another concern associated with dry-out in the STAs (as in other south Florida wetlands) is the potential for mercury methylation upon rewetting (SFER, 2007 Appendix 5-5, Appendix 3B-2; SFER, 2008, Appendix 5-7, Appendix 3B-3; SFER, 2009 Appendix 5-4). For these reasons, avoidance of dry-out continues to be an important management strategy for STAs.

Operation of Stormwater Treatment Areas: Vegetation Management

Effective management of both desirable and undesirable vegetation within the STAs is critical to achieving and sustaining the required treatment performance (Gary Goforth, Inc., 2005; Malcolm Pirnie, Inc., 2008). The SFWMD routinely applies herbicide in the STAs for exotic/nuisance species control and has found that the most effective control of non-desirable vegetation is achieved through proactive vegetation management. This is particularly critical for floating aquatic vegetation (FAV) which can shade out and impact SAV. The SFWMD has successfully implemented SAV inoculation efforts using equipment on the land, in the water and in the air (helicopter) (Malcolm Pirnie, Inc., 2008, pg 3-13) (***Figure 3-3).***

Operation of Stormwater Treatment Areas: Operational Envelopes

The original design of the STAs was based on a simplified P removal model and annual-average flow and P data. Because this design approach did not consider the temporal/seasonal characteristics of the inflows, there was little reference against which actual inflows and resulting STA performance could be assessed (SFER, 2009, pg 5-16). By contrast, the Long-Term Plan Enhancements were designed using a 36-year set of simulated daily flows and P loads and the Dynamic Model for Stormwater Treatment Areas (DMSTA). This approach captures the variability of inflows and provides a reference against which actual inflows can be compared to the predicted inflows. DMSTA relies on data from approximately 80 experimental wetland treatment platforms, test cells, and full-scale demonstration cells, and natural wetlands. Additional information on the DMSTA model can be obtained by visiting the DMSTA website (www.wwwalker.net/dmsta), or contacting the developer Dr. William W. Walker. Using the results of the DMSTA modeling, STA Operational Envelopes were developed to account for the variable inflows the STAs receive. Weekly summaries comparing the actual inflows to the Operational Envelopes are used to try to ensure that the STAs are not subject to overload of either flow or P while taking into account the SFWMD's overall water management obligations, including managing water for flood protection, water supply and natural systems (SFER, 2009, pg 5-16). In addition, the SFWMD monitors stages in the treatment areas on a daily basis and uses this information for operational decision-making. This is particularly important in EAV cells which can be negatively impacted by extended periods of high stages resulting in widespread cattail damage and loss, which then results in reduced P treatment performance.

Design of Stormwater Treatment Areas - Public Access

In fulfillment of the public access and recreation requirements of the EFA, recreational facilities have been constructed at several of the STAs. Recreational activities in and around the STAs have provided significant benefits to the public while being fully compatible with the water quality goals of the STAs (SFER, 2009, pg 5-4).

Stormwater Treatment Area Performance Optimization Activities and Research

Substantial progress toward reducing phosphorus levels discharged into the EPA has been made by the State of Florida and other stakeholders. Since inception and through April 30, 2009, the STAs retained more than 1,200 metric tons of TP that otherwise would have entered the Everglades (SFER, 2010). However, additional measures are necessary to achieve the Everglades water quality goal. Extensive monitoring and research activities underway in the STAs since the development of the Everglades Nutrient Removal Project (ENR) have provided valuable information in support of refinements to the performance of the STAs (See STA Chapters of 2005 through 2010 SFER; STA Chapters of 1999-2004 ECR). Many factors can impact STA performance, such as variability in inflows, antecedent land use, inflow water chemistry, inflow water TP concentrations, vegetation composition, soil type, cell topography, cell size/shape, hurricanes, major storms, droughts, and regional operations. While much has been learned about STA performance and optimization, the SFWMD is committed to implementing the necessary strategies to achieve compliance with water quality standards. For this reason, in addition to continuing to research ways to further improve STA performance, the SFWMD is currently evaluating improved upstream source controls, STA expansion, upstream storage/flow equalization, and operational refinements. In addition, monitoring and research in the areas downstream of STA discharges has been underway since discharges began. In Water

Conservation Area (WCA) 2A downstream of STA-2 discharges, results indicate that there have been improvements at several previously nutrient-impacted sites, and there was generally no negative impact at previously unimpacted sites in WCA 2A resulting from STA-2 discharge. The benefits include increased hydroperiod and improved water quality, as evidenced by decreased surface water TP concentrations, decreased or steady soil TP concentrations, increased relative abundances of low nutrient periphyton indicator species, decreased relative abundances of high nutrient periphyton indicator species, and decreased nutrient content in periphyton tissues (Garrett and Ivanoff, 2008).

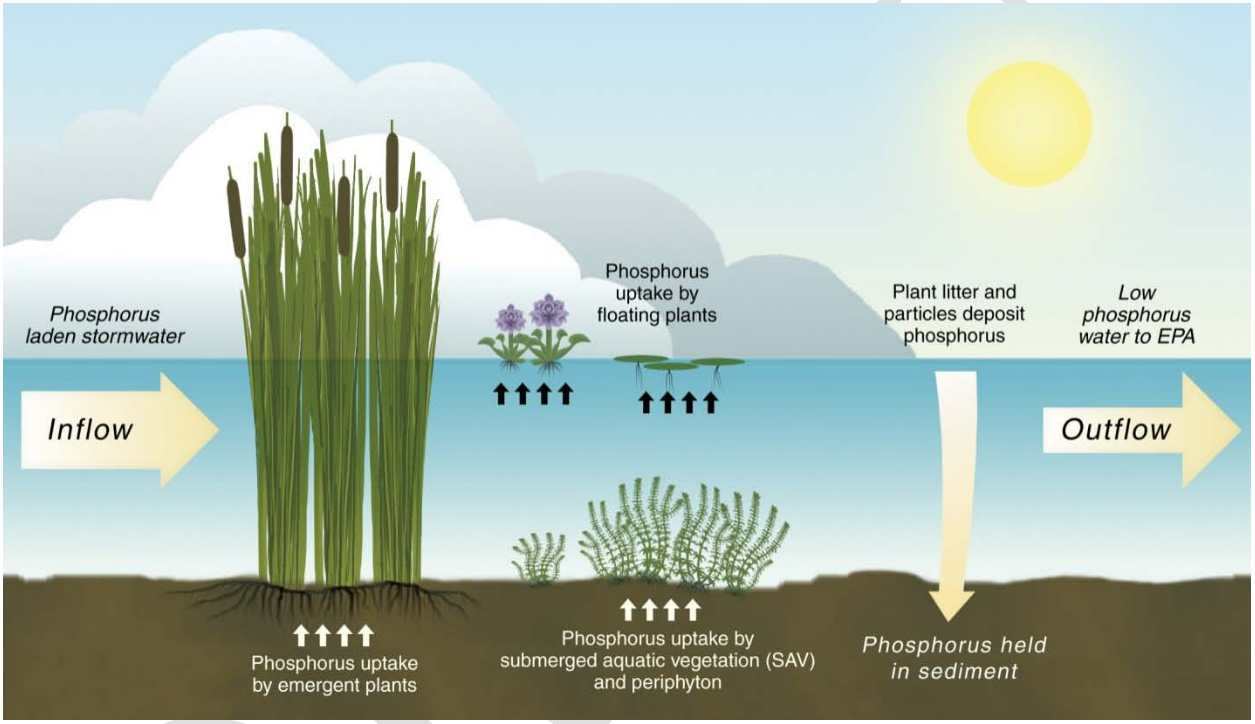

FIGURE 3-2: SCHEMATIC SHOWING STORMWATER TREATMENT AREA TREATMENT TRAIN

FIGURE 3-3: SUBMERGED AQUATIC VEGETATION DROP FROM HELICOPTER

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3.2.2 Non-structural Methods: Best Management Practices

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Lake Okeechobee Watershed Best Management Practices Evaluation

The South Florida Water Management District (SFWMD), Florida Department of Environmental Protection (FDEP), Florida Department of Agriculture and Consumer Services (FDACS), and other organizations have worked cooperatively to undertake an array of state and local projects to implement agricultural and urban best management practices (BMPs) in the Lake Okeechobee Watershed for reducing total phosphorus (TP) loads to Lake Okeechobee (SFWMD et al., 2004; SFWMD et al., 2007; SFWMD et al., 2008). These BMP implementation projects have reduced phosphorus (P) transport from uplands and captured runoff during high rainfall periods. Examples of the most commonly implemented types of BMPs in the watershed include the improvements of on-site storm water management systems, the installation of on-site water detention/retention facilities, and wetland restoration and enhancement. The detailed project description and results are included in Volume I, Chapter 10 of the South Florida Environmental Report (www.sfwmd.gov/sfer). A brief summary of major projects implemented in the Lake Okeechobee watershed is provided below.

In October 2000, the SFWMD initiated the dairy Best Available Technology (BAT) projects to identify, select, and implement various technologies to significantly reduce TP discharge from dairy operations in the Lake Okeechobee Watershed. These BAT projects consist of (1) capturing stormwater runoff (especially from all of the high-nutrient pasture areas), (2) reusing the runoff on-site in current operations if possible, and (3) if off-site discharge is necessary, chemically treating the stormwater prior to its release to reduce nutrient load. Three dairy BAT projects are fully constructed, and performance monitoring was initiated in May 2004 and a fourth site was completed in December 2005. The performance monitoring and evaluation phase was completed in June 2008 (SWET, 2008a). The annual TP load reductions ranged from 0.19 to 1.62 metric tons. These sites used retention and reuse followed by chemical treatment to achieve reduction rates ranging from 66-100 percent. Drought conditions contributed to the high P load reduction rates via solely retention/reuse during these two years.

The Florida Ranchlands Environmental Services Project (FRESP) is intended to design a program in which ranchers in the Northern Everglades sell environmental services of water retention and TP load reduction to agencies of the state and other willing buyers (http://www.worldwildlife.org/what/globalmarkets/agriculture/FRESP.html). These ranches can bring services online quickly as compared to other options and are planned to complement public investment in regional water storage and water treatment facilities. The sale of the services is expected to provide additional income for ranchers that face low profit margins and to provide an incentive against selling land for uses that could further aggravate water flow, pollution, and habitat problems. FRESP is being implemented through collaboration among the World Wildlife Fund, eight participating ranchers, Natural Resources Conservation Service (NRCS), FDACS, SFWMD, and the FDEP. As of July 2009, seven FRESP water management projects have been designed, constructed, and are being monitored to capture hydrological and chemical data and one remains under construction. Data collection started in 2007 on four of the ranches and is planned to continue on all eight through the end of the pilot project in 2011. Projects include rehydrating drained wetlands, water table management, and pumping water from a nearby off-site canal through the existing ranch and then letting the treated water gravity-flow back into the canal. The eight ranchland water management projects occupy approximately 8,500 acres, not including drainage acres. A planning level estimate of the static water-retention capacity of the eight projects is 8,260 acre feet (1,019 hectare meters) of water for a single storm event with an average storage depth of 0.98 feet (0.3 meters).

To assess the effectiveness of the agricultural BMPs on load reductions, the Watershed Assessment Model (WAM) (SWET, 2009) has been applied to the Lake Okeechobee Watershed. WAM is a Geographic Information System (GIS)-based hydrological and water quality model. Baseline simulations of each drainage basin were performed to represent existing conditions. Each land use was assigned parameters to represent current fertilization and water management practices that affect water quality. Those parameters are the input to field-scale hydrologic models, Groundwater Loading Effects of Agricultural Management System (GLEAMS) and/or Everglades Agricultural Area Model (EAAMOD). Three management "what if" scenarios were simulated: (1) agricultural and urban BMPs; (2) all BMPs simulated in scenario one plus the existing source control and regional projects; and (3) all BMPs and projects simulated scenario two plus the regional stormwater treatments systems ([STAs] and reservoir-assisted STAs). The net nutrient-load reductions to Lake Okeechobee for the three scenarios as compared to the baseline run are approximately 72, 84, and 114 metric tons of TP per year and 1,180, 1,200, and 1,390 metric tons per year of total nitrogen (TN) across all of the basins north of Lake Okeechobee, respectively. The major advantages of the WAM model simulations is that they now provide much better spatial depiction of nutrient sources and transport processes. This expanded knowledge should allow for additional refinement to the nutrient abatement strategies within the Lake Okeechobee Watershed.

A critical component in the success of the BMP program is the verification of BMP implementation through inspection and records review, and collection and analysis of data to determine whether the BMPs are working as anticipated. The baseline conditions and long-term water quality trend pertaining to P and nitrogen (N) concentrations are being studied (Zhang et al., 2009). A total of 51 monitoring stations were studied: 35 long-term, ambient monitoring stations that included 27 stations within the four high TP contributing basins and eight along the Kissimmee River; and 16 stations located at the outfalls of the dairy operations. Only TP data were collected at the 16 dairy stations. The baseline data and trend analysis for TP and TN concentrations were summarized at the basin level using the data collected at the 35 long-term, ambient monitoring stations. Among the 27 long-term, ambient monitoring stations, five stations had a significant decreasing trend, while eight stations showed a significant increasing trend in terms of mean monthly TP concentrations. Among the 16 dairy stations, 11 stations displayed a decrease in TP concentrations and six of these stations had statistically significant decreasing trends. The implementation of dairy best available technologies, wetland restoration, and other TP control projects has contributed to the reduction in the concentrations at these dairy monitoring stations.

Although BMPs have been initiated to a certain degree, there is still a large percentage of the watershed that needs dedicated resources in order to realize the full level of BMP implementation needed for nutrient reductions. T he high levels of legacy P in the soils play a role in the delayed response of the watershed to show TP concentration reductions. A recent study of legacy P in the watershed concluded that there is an abundance of mobile legacy P present, which can maintain elevated P levels going to Lake Okeechobee for many years (SWET, 2008b). This conclusion was derived based on previous research conducted by the University of Florida and others (Graetz and Nair, 1995; Reddy et al., 1996; Steinman et al., 1999; Hiscock et al., 2003). Therefore, the reduction through abatement practices of new sources of P and its mobility to Lake Okeechobee will be an effective means of addressing P loads in Lake Okeechobee. In summary, more aggressive nutrient control measures, including full BMP implementation, still need to be implemented in all the surrounding basins that discharge to the lake in order to reach the lake's total maximum daily load (TMDL) goal of 140 tons of P per year (including the atmospheric load of 35 tons per year) (FDEP, 2001).

Nutrient Source Controls in Other Watersheds

BMPs (or Source Controls) play a part in achieving reductions in P loads to the priority surface waters and with the enactment of the Northern Everglades and Estuaries Protection Program (NEEPP) will also reduce N loads to the Caloosahatchee River and St. Lucie River Estuaries. The coordinating agencies oversee implementation of BMPs for agricultural, urban and industrial use. A critical component in the success of the BMP program is the verification of BMP implementation through inspection and records review, and collection and analysis of data to assess collective source controls performance. Information about the results of BMPs is contained in Volume I, Chapter 4 of the South Florida Environmental Report (SFER). The 2010 SFER can be found at www.sfwmd.gov/sfer.

Caloosahatchee and St. Lucie River Watersheds

- SFWMD completed the Caloosahatchee River Watershed Protection Plan (CRWPP) and St. Lucie River Watershed Protection Plan (SLRWPP) and submitted the plans to the Florida legislature in January 2009. The protection plans present the overall strategy to reduce nutrients from the watersheds through the implementation of pollutant source control programs and efforts, including a regulatory nutrient source control program.
- SFWMD completed the conceptual project plan, in follow-up to the CRWPP and SLRWPP, describing the planned phases, funding needs, and activities leading up to the establishment of a regulatory nutrient source control program for the St. Lucie and Caloosahatchee River watersheds.
- Initiated contracts and secured resources to begin a synoptic wet season monitoring program during water year (WY)2010 for tributary streams within the freshwater portion of the Caloosahatchee River Watershed (a task under a water quality monitoring phase of the conceptual project plan for implementing the regulatory nutrient source control program).

Southern Everglades Nutrient Source Controls Update

The Southern Everglades covers the SFWMD P source control efforts in the Everglades construction project and non-Everglades construction project basins during WY2009 and includes basin-specific reporting of compliance status, P levels and monitoring data, and source control strategies as indicators of success. The EAA continues to meet the required performance levels of the Everglades Forever Act (EFA) with a 68 percent TP load reduction in WY2009. For the C-139 Basin, WY2009 marks the seventh year of mandatory BMP implementation; however, TP loading requirements were not met and the basin was deemed out of compliance. The C-139 Basin Rule is being amended to include more stringent BMP requirements. It should be noted the SFWMD continued to monitor the discharges from each non-Everglades construction project basin to evaluate the effectiveness of source control strategies and to track the direction of compliance with the TP concentration limits for the C-111 Basin and the water quality trends for the C-11 West, North New River Canal, Feeder Canal, and L-28 Basins. It is expected that the EFA long-term compliance permit, also referred to as the post-2006 Phase II permit, will contain TP limits for the non-Everglades construction project basins. The SFWMD expects that the Phase II permit will be issued during WY2011.

Several factors regarding BMP effectiveness have been identified as a result of the monitoring being performed in the ECP and non-ECP Basins as well as BMP research. The research includes projects such as the C-139 Basin Vegetable Production Demonstration Project to optimize P application rates in vegetable fields and the C-139 Basin BMP Demonstration and Effectiveness Grant (demonstration grant) whose focus is on innovation or optimization of traditional BMPs that are presumed to be effective in removing P, focusing on implementation techniques that will result in the greatest water quality improvement under the basin-specific conditions. The factors include:

- BMPs selected for a plan should include water management, nutrient control practices, particulate matter and sediment controls, and pasture management (if applicable) to ensure control of different P species and transport mechanisms. Addressing the different P species and transport mechanisms is key. This increases the potential for success in TP load reduction under varying environmental and farming conditions.
- The traditional technical knowledge of BMPs needs to be expanded to assist growers with basin-specific implementation practices.
- Keys for successful BMP optimization require that technical documentation be developed and field verified through BMP demonstration and research, both at the regional level and on a site-specific basis. BMP optimization must also be based on results from an optimized water quality and quantity monitoring network and by targeting the BMPs that are designed to improve water quality for specific situations.
- Patience must be exercised after BMPs have been implemented for improvements to be realized. TP load reductions appear gradually and progress may be impacted by weather trends such as drought or extremely wet conditions. In essence, assessment timeframes need to allow for BMPs to translate into P loading reductions.
- Initial and on-going verification that BMPs are being implemented and maintained is necessary to confirm that P performance measures in terms of reducing P loads from an area are being achieved.

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4 EVERGLADES HABITATS: KNOWLEDGE GAINED

This section of the Scientific Knowledge Gained (SKG) document addresses the following component identified by the Committee for Independent Scientific Review of Everglades Restoration Progress (CISRERP) as critical for Everglades restoration (NRC, 2006; NRC, 2008):

> Retention, improvement, and expansion of the full range of habitats by preventing further losses of critcal wetland and estuarine habitats and by protecting lands that could usefully be part of the restored ecosystem.

4.1 Landscapes, Key Habitats, and Endangered Species

The following topic summaries are under the heading "4.1 Landscapes, Key Habitats, and Endangered Species":

4.1.1 Phosphorus-related Biogeochemical Processes in Ridge and Slough Landscapes

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A tremendous quantity (likely approaching $100 million) of research has focused on the biogeochemistry of Everglades wetlands in the last two decades, mostly to define water quality rules for the Clean Water Act, to design and operate the South Florida Water Management District's (SFWMD) regional network of stormwater treatment areas (STAs), to rehabilitate the nutrient impacted regions of Water Conservation Area 2 (WCA 2) through the Cattail Habitat Improvement Project (CHiP) at the SFWMD, and to gain basic scientific understanding of the system. These research programs focus on identifying, understanding, managing, and/or buffering the ecological impacts of nutrient pollutants in south Florida's surficial waters. The various research programs conducted in Everglades marshes retained the pattern present in the historical system, have lost pattern (sensu Wu et al., 2006) and are either actively losing peat soils to oxidation, or stabilized (no longer losing soil organic matter), as well as in wetlands created and developed for removal of phosphorus (P) from agricultural runoff. Key findings from these research efforts which have been published in peer reviewed scientific journals form the substance of this brief summary report.

Key Findings of Nutrient Cycling Processes

At the beginning of the decade, Noe et al. (2001, 2002) had already begun to synthesize data of many investigators who focused on Everglades biogeochemistry and reported the rapid incorporation of low-level P concentrations into algal communities and marsh plants in a flume experiment. Both of these results supported the concept that Everglades wetlands are strongly P limited, and by tracing the path of radioisotope P through the chemical and biological sorption pathways Noe et al. (2003) were able to identify potential mechanisms which could be manipulated to systematically remove non-point source P in managed treatment wetlands. These research projects also served as a basis for developing expectations for P movement through the living and non-living portions of the ecosystem. Research that was focused on taking the next step of relating P cycles to both fluid dynamic processes in the Everglades wetlands (Harvey et al., 2005; 2009) and marsh habitat development feedback processes (Larsen et al., 2007; Hagerthey et al., 2008) identified the essential role that submerged aquatic vegetation (SAV) in sloughs and benthic algal floc layer (BAFL) communities play in the physical capture and transfer of dissolved solutes from the water column into emergent marsh vegetation, bacterial, and algal communities. These findings led to the conclusion that microbial communities associated with the soil, flocculent organic material, and periphyton mats control P-cycling in the oligotrophic everglades (Noe et al., 2007). It is no mistake that these same components of the ridge and slough habitats are commonly identified as excellent indicators of nutrient impacts (Gaiser et al., 2004; Iwaniec et al., 2006; Hagerthey et al., 2008, Wright et al., 2009), in contrast to water total phosphorus (TP) concentrations which do not appear to be informative in the early stages of nutrient enrichment impacts (Iwaniec et al., 2006) because water column concentrations can be so variable in comparison to concentrations of P in biological or soil compartments of the marsh.

Research conducted in the last decade built upon a significant amount of pre-existing knowledge about dynamics (defined as the physical motivating or driving forces) of P in a wetland. While water quality improved in the 1990s, the spatial extent of wetland habitat exhibiting impacts from eutrophication increased, indicating the lagging effects of nutrient loading which should be expected to continue for years after polluted waters are stopped from entering the ecosystem (Childers et al., 2003). Both lag effects and soil oxidation processes are likely to account for the continued expansion of nutrient impacted soils in WCA 3 from 1992-2003 (Bruland et al., 2007).

In the eutrophic STAs it has been demonstrated that both the P concentrations of outflow waters, and the fraction of TP found complexed with particulate carbon, increase when P loading in STAs exceeds 1.3 g m^{-2} yr^{-1} (i.e. when the STA is overloaded) (Dierberg and DeBusk, 2008). Downstream of the STAs, in WCA 3A, flocculent sediments and soils demonstrate higher TP concentrations (milligrams per kilograms [mg/kg]) near water-inflow points than far away from these points. Soil oxygen demand is greater in nutrient impacted areas, methane production is the most sensitive indicator of eutrophication of the three possible indicators (soil oxygen demand, carbon dioxide production, and methane production) and methane production increases as TP in soils increases (Wright et al., 2009).

Soil and floc TP concentrations, microbial biomass P and mineralized P are good indicators of nutrient loading in WCA 1, 2, 3, and Taylor Slough. While total nitrogen (TN) and TP loading are often correlated, spatial patterns for TP and TN are very different, with TN being much more variable over short spaces (Grunwald and Reddy, 2008). This spatial pattern is probably associated with the presence of denitrification and nitrogen fixing processes which either add or remove N, while P has no gaseous form.

Givnish et al. (2008) identified a correlation between the presence of tall tree islands and tall sawgrass marshes, a previously unidentified property of ridge and slough habitats. While Penton and Newman (2008) discovered increased activity of enzymes participating in decomposition in eutrophic conditions. Enzyme activities indicate that decomposition rates are faster in slough environments than ridges, and enzyme activity is higher at the soil surface (described as benthic in the paper) than below the soil surface.

Finally among the most important of developments with respect to ridge and slough biochemistry is a theoretical framework for inferring causal mechanisms driving the formation of patterned wetlands (Eppinga et al., 2009). While this paper was focused on temperate patterned peatlands, there are important generalized applications which have been tested as hypotheses in Everglades ridge and slough areas. Clark et al. (2009) sampled soil TP concentrations in adjacent ridges and sloughs and concluded that formation of ridge/slough patterns probably depend on nutrient redistribution from ridges to sloughs rather than differential transpiration (which operates in arctic peatlands). The result of this test of hypotheses agrees with work conducted by Larsen et al., (2007) that was focused on oligotrophic ridge and slough. Larsen et al. (2007) concluded that particle capture by the seasonally inundated sawgrass ridges likely plays a more dominant role in the attainment of hydraulic efficiency and equilibrium (both desirable characteristics of a ridge and slough landscape), where hydraulic efficiency is defined as the ability of a given flow volume to transport sediment (similarly, maximum flow efficiency, as defined by Huang and Nanson [Earth Surface Processes and Landforms, 2000]) is the maximum sediment transport capacity per unit of available stream power, where stream power is proportional to the product of water-surface slope and discharge). It will be interesting to observe how the next decade of research might progress from the existing understanding of biogeochemical processes to a working knowledge of how to manage these processes so that they enhance the rate of recovery of our existing degraded habitats.

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4.1.2 Tree Islands and Everglades Restoration

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Water management has altered the physiognomy of tree islands, reduced their numbers and spatial area, altered vegetation dynamics, and changed wildlife habitat. The number of tree islands in the Everglades declined 61 and 87 percent in Water Conservation Areas (WCAs) 3 and 2A, respectively, between 1953 and 1995 (Sklar and van der Valk, 2002b). Tree islands are important Everglades components, as both habitat and as an influence on landscape and ecosystem processes. Consequently tree islands research has expanded dramatically since 1999 to include island formation, ecology, landscape patterns, and nutrient dynamics.

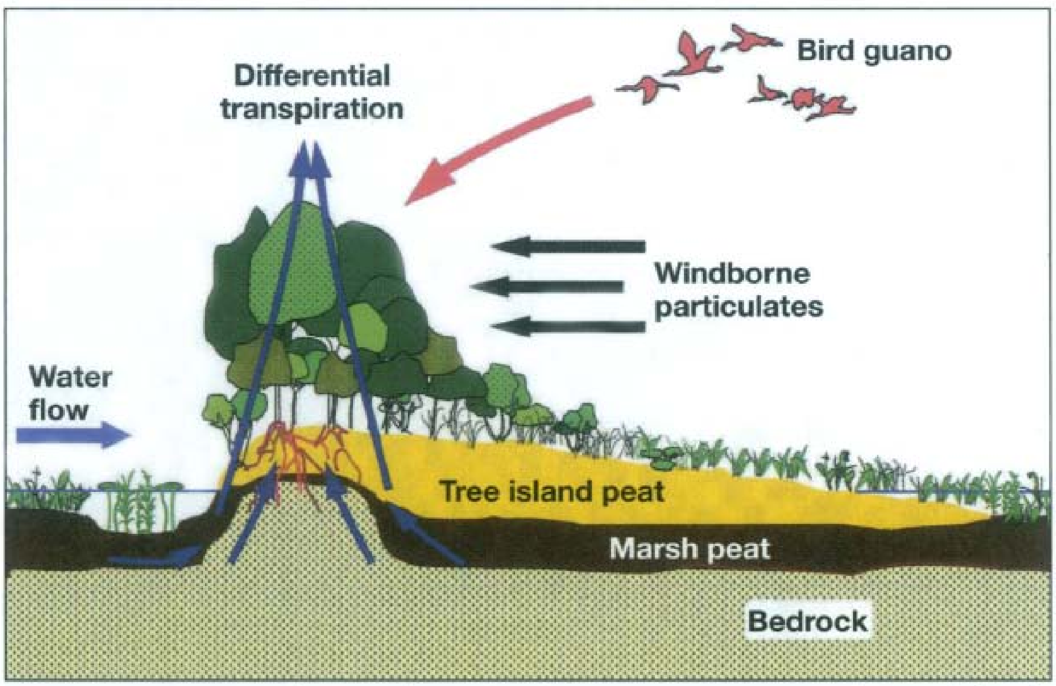
Tree Island Formation

Peat formation in the Everglades began approximately 5,000 years before present (YBP) in the northern Everglades and approximately 2,000–3,000 YBP farther south (Gleason and Stone, 1994). The peat complex formed as a result of limestone development over basement rock and sandy ridges that confined the drainage (Gleason and Stone 1994). Tree islands appeared between 3,500 and 500 calibrated YBP, depending on the location in the Everglades (Willard, 2006).

Although variable over time, tree island appearance correlates with multi-decadal drought intervals (Willard et al., 2006). Islands can form as blocks of floating peat, over depressions in bedrock, or on fixed, topographic highs (Sklar and van der Valk, 2002; Willard, 2004; Lodge, 2005; Willard et al., 2006; Givnish, 2008). Islands may even develop from human middens (van der Valk and Sklar, 2002). Givnish et al. (2008) proposed four primary mechanisms of tree island formation: peat accretion due to positive feedback on raised land surface, woody plant establishment and phosphorus (P) enrichment due primarily to bird droppings, shifts in differential peat accretion caused by differences in plant species composition and P dynamics, and changes in elevations that result from increases due to peat accumulation and decreases due to burning and oxidation of peat. Richardson (2009) and Givnish (2008) describe the Everglades as a peatland on which topography changes as a result of water level changes and subsequent accumulation and decomposition responses. These changes in elevation and peat accumulation and decomposition are consistent with decreasing peat thickness from head to tail on fixed islands and the absence of a clear relationship between vegetation and peat and bedrock elevations (Mason and van der Valk, 2002). The large area and time frame over which the Everglades developed suggest that system responses to restoration may be slow (Willard, 2004; Richardson, 2009). Givnish et al. (2008) conclude that changes in the relationship between tree island communities and water regime appear to reflect a lag of a few years following shifts in water management, with longer lags expected for shifts in landscape patterns.

Tree Island Features

Thousands of tree islands cover less than five percent of the Everglades (Gleason and Stone, 1994; Sklar and van der Valk, 2002; Jones, 2006). Island shape and orientation reflect pre-drainage flow direction and velocities (Brandt, 2002; Willard, 2004; Bazante, 2006; others), nutrient gradients (see discussion below), and fire (Sklar and van der Valk, 2002). Since 1999, several studies of island vegetation and diversity have been completed (Heisler et al., 2002; Arementano et al., 2002; Brandt et al., 2003; Gann and Childers, 2006; others). The ten-year mean water level and time since last burn were identified as the most important factors explaining changes in tree island vegetation (1977-1986) by Wetzel (2002). Studies of the effects of flows on islands (Bazante et al., 2006) show that higher water velocities entrain water around tree islands and form channels. The process is facilitated by tree canopy that shades submerged vegetation, while vegetation in turn decreases flow resistance and sediment deposition. Together, these actions limit the areal extent of tree islands. Wu et al. (2002) successfully predicted tree island loss in WCA 2 based on water depths greater than 30 centimeters and duration greater than 150 days. With the exception of wading birds (see Sklar and van der Valk, 2002), wildlife studies of islands remain limited in number and taxa (Meshaka et al., 2002). Tree islands have been used by humans for centuries (Carr, 2002) and currently are an important cultural resource used by the Miccosukee Tribe of Indians of Florida.



Source: Wetzel et al. 2005

FIGURE 4-1: MAJOR MECHANISMS THAT REDISTRIBUTE NUTRIENTS FROM MARSHES AND SLOUGHS TO TREE ISLANDS IN THE EVERGLADES

Tree Island Patterns

Changes in size and shape of tree islands in the Everglades are consistent with changes in hydrologic patterns modeled for pre- and post-drainage conditions (Brandt et al., 2000). Over the past several decades, the number of small tree islands has declined and the remaining larger islands have been isolated (Hofmockel, 2008). The result has been loss of habitat diversity that would otherwise provide resilience (ability of the system to recover following disturbance) (Meffe and Carroll, 1994; Gunderson, 2000). The decline in tree islands in the central

Everglades (WCAs 2 and 3) has been attributed to prolonged high water levels (Newman et al., 1998; Willard, 2002; Jones et al., 2006; Wu et al., 2006; Hofmockel et al., 2008). In contrast, islands in Shark River Slough have expanded in size due to water diversions (Willard et al., 2006). Loxahatchee National Wildlife Refuge (WCA 1) in the north Everglades retains much of the heterogeneity of the historic Everglades (Willard, 2004; 2006; Richardson, 2009), and much work has focused the north-south pattern differences. Geographical information system (GIS) and aerial photography document the effects of large-scale processes (i.e., water regime) on tree island patterns (Patterson and Finck 1999; Brandt et al., 2002; Willard et al., 2006; Hofmockel et al., 2008; Rutchey, 2008). While water depth alone is strongly correlated with vegetation on islands and is a key driver of plant composition and succession (Gunderson and Loftus, 1993; Jordan et al., 1997; Heisler, 2002; others), recent studies emphasize the importance of combined local (water depth and correlated factors) and landscape scale (proximity to tall tree islands) gradients in driving tree island patterns (Givnish et al., 2008). Historically, frequent, wet season fires burned marsh but not tree islands, maintaining the integrity of the tree islands in the landscape (refer to fire ecology paper). In addition, the regional differences in relationships of vegetation to water regime appears to lag a few years behind shifts in water management: a longer lag would be expected for shifts in landscape patterns (Givnish et al., 2008).

Phosphorus

An estimated 67 percent of P entering the pre-drainage central Everglades was sequestered on tree islands (Wetzel, 2009), suggesting that island loss may also reduce an important P sink in the Everglades (Wetzel, 2005; Hanan and Ross, 2010; Troxler and Childers, 2010). In addition, increased flows may increase mineralization of organically bound P and nitrogen (N) in soils and increase nutrient loads downstream (Gann et al., 2005). Soil P levels on islands can be 100 times higher than in the surrounding marshes and sloughs (Orem et al., 2002; Willard et al., 2003; Jayachandran et al., 2004; Wetzel et al., 2005; Hagerthey et al., 2008). These biogeochemical hotspots (Wetzel et al., 2005; 2009) may be responsible for the oligotrophic conditions of the Everglades, despite large natural inputs from birds, predators (***Figure 4-1***) (Wetzel et al., 2005; 2009), and human middens (Coultas et al., 2008). Downstream tails of tree islands often have higher sawgrass productivity due to P release from island heads, and burned tree islands can pulse P downstream (Givnish et al., 2008; Richardson, 2008). P transported downstream (Sklar and van der Valk, 2002; Wetzel et al., 2005) influences vegetation (Troxler-Gann et al., 2005; Richardson, 2009) and nutrient distributions (Childers et al., 2003; Hanan and Ross, 2009). Wetzel et al. (2005) and Ross et al. (2006) suggest that the concentration of nutrients on islands is due to ground water pumping via high evapotranspiration rates and suggest other mechanisms including dry fallout deposition, guano deposition, and bedrock mineralization by tree exudates (Wetzel et al. 2005). Givnish et al. (2008) reject the evapotranspiration mechanism due in part to the high hydraulic conductivity values needed to support such a mechanism. The slow pace of the P interactions is emphasized by high P levels that have persisted decades after the loss of 90 percent of the wading birds in the Everglades (Ogden, 1994; Wetzel et al., 2005).

Restoration

Tree islands are regional-scale indicators of the Everglades landscape (Wu et al., 2002; Willard et al., 2006; Gann and Childers, 2006; Richardson, 2009; others). Scientists agree that the slow, large scale processes that formed islands may explain the landscape pattern that persists despite large scale hydrologic changes (Willard, 2002; Givnish, 2008; Richardson, 2009). Restoration efforts should, therefore, accommodate factors that indirectly (e.g., increased period of flooding) and directly (e.g., increased fires) affect tree islands (Wetzel, 2009). Separating the influence of primary climate-driven factors (e.g., rainfall, hydroperiod, and fire from the secondary human factors of drainage and flooding, nutrient additions, site disturbance, and non-native species invasions remains a challenge for restoration efforts) (Richardson, 2009).

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4.1.3 The Significance of Oligohaline and Mesohaline Habitat in the Southern Coastal Systems

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Salinity is identified as a stressor in all conceptual ecological models (CEMs) developed for Florida's estuaries and adjacent mangrove wetlands (Browder et al., 2005a; Davis et al., 2005; Ogden et al., 2005; Rudnick et al., 2005). Salinity was identified as the most important physical parameter for determining species and community composition in coastal waters (RECOVER, 2009). Lorenz and Serafy (2006) found that the coastal wetland ecosystem of Florida Bay was less productive than pre-drainage conditions resulting in declines in the resident demersal forage fish community and, as a result, declines in populations of predatory species that forage in the estuary (e.g., piscivorous fishes, alligators, crocodiles, and wading birds). Increasing freshwater flows should result in reestablishment of zones of lower salinity in the coastal wetlands and the return of the prey base and the predator populations that depend upon them (Lorenz and Serafy, 2006). In addition, restoration of a positive salinity gradient from the freshwater marshes to the bay should restore oyster habitat and other habitat of fish and invertebrate species that depend upon the marshes, mangroves, or nearshore bay for all or some part of their life cycle.

The desired restoration condition throughout the southern coastal system (south Biscayne Bay, Manatee Bay, Barnes Sound, coastal Florida Bay, Whitewater Bay, and the southwest coast riverine area up through the Ten Thousand Islands area) is the presence of oligohaline (less than 5 practical salinity units [psu]) habitat within the coastal lakes and basins within the mangrove transition zone and a broad, persistent mesohaline (less than 18 psu) habitat in the nearshore zone (Note that the nearshore zone can vary with location being open water shoreline in the bays [e.g., Florida Bay, south Biscayne Bay] and being within mangrove lined rivers and bays along the southwest coast). Water management practices have reduced freshwater flows through the mangrove transition area to all of the southern coastal system of the Everglades and caused alternation between exceptionally high flows for relatively short periods and long periods of no flow, creating abnormally large fluctuations in both flow rates and salinity. The combined result is a contraction or elimination, and general instability, of oligohaline and mesohaline areas within the coastal wetlands and along the coastal fringe, where the shoreline habitat and shallow vegetated bottom habitat, so favorable to small forage fish and invertebrates and their predators, are found.

The CEM for the mangrove transition zone (Davis et al., 2005) describes the pre-drainage hydrologic condition in the southern Everglades as producing pooling of freshwater immediately upstream of the mangrove estuaries and prolonged durations of freshwater flow into the estuaries. The freshwater pooling attenuated flows between wet and dry seasons and years, creating wide, slowly fluctuating salinity gradients, and supporting a broad oligohaline zone within the mangrove estuaries, two elements that are missing today.

The Biscayne Bay CEM describes a salinity regime of slow, relatively predictable variation incorporating a relatively broad salinity gradient that includes oligohaline wetlands and mesohaline habitat along the shoreline prior to canal development and drainage (Browder et al., 2005). The loss of oligohaline habitat has resulted in the loss of the associated fish community resulting in the loss of that habitat and food source for piscivorous fish and wading birds. The contraction of the oligohaline and mesohaline zones has resulted in a loss of diversity of aquatic habitat. Within the coastal wetlands upstream of Barnes Sound and Manatee Bay the upstream encroachment of saline water has resulted in the development of the "white zone", a band of low productivity between the present brackish and freshwater wetlands (Browder et al., 2005).

The Florida Bay CEM (Rudnick et al., 2005) restoration is described as expanding the extent and duration of oligohaline to polyhaline conditions, while decreasing the extent and duration of hypersaline conditions.

The salinity performance measure for all areas of the southern coastal systems, south Biscayne Bay to the southwest riverine coast, considers restoration to be the existence of oligohaline conditions in the mangrove transition area and the coastal lakes and an expanded mesohaline area along the shoreline seaward of the mangrove fringe. Restoration is described as a persistent mesohaline zone along the shoreline that expands in area during the wet season and continues to exist, although at a reduced size, throughout the dry season. This habitat has been lacking from the system for such an extended period of time that the estuarine species dependent on these areas have been eliminated or are in very low numbers.

The reduced volume and duration and high variability of flow into the mangrove transition area has stressed submerged aquatic vegetation (SAV) and reduced its spatial and seasonal coverage. The result has been the contraction or elimination of SAV commonly found in brackish or oligohaline habitat--species such as shoal grass, widgeon grass, bladderwort, and southern naiad and fresh macroalgal species including muskgrass (Madden et al., 2009). In the SAV performance measure the desired condition in Florida Bay is to recover seagrass beds over most of bay bottom, extending west along the Gulf of Mexico coastal shelf to Lostman's River, and to restore a diverse mosaic of turtle grass, shoal grass, widgeon grass and manatee grass seagrass communities. The desired condition for south Biscayne Bay is to increase the cover of seagrass beds consisting primarily of species tolerant of lower salinities, e.g., shoal grass, in nearshore areas that presently lack persistent seagrass communities. The desired condition in the Everglades mangrove estuaries is to increase cover and seasonal duration of shoal grass, muskgrass, southern naiad, and bladderwort in coastal lakes and basins.

The technical documentation to support development of minimum flows and levels (SFWMD, 2006) uses widgeon grass as an indicator of SAV habitat and ecosystem status within the transition zone. This species and associated SAV are important to fauna as food source and refuge, supporting a number of faunal species that inhabit the zone either transiently or as resident species (Ley and McIvor, 2002; Lorenz et al, 2002 in SFWMD, 2006). Other important ecosystem functions of widgeon grass and associated species area listed in the technical documentation (SFWMD, 2002). The technical documentation reported that widgeon grass was sensitive to freshwater inflow, exchanging dominance with muskgrass, southern naiad and bladderwort as conditions became fresher (more oligohaline) and with shoal grass as conditions became greater than 20 psu (more polyhaline). The Miami-Dade Department of Environmental Resources Management (DERM) Fish Habitat Assessment Program (FHAP) sampling of seagrass data in the transition zone showed expansion of the freshwater and brackish water plant assemblages with higher freshwater flows into this zone from the start of data collection in 1995 until the 2005 reporting (DERM, 2005). In a summary of SAV data, Madden et al. (2009) found that widgeon grass was absent in this zone during low freshwater inflow periods after 2005.

The constricture of salinity gradients in the southern coastal systems has greatly affected the fish communities within those areas. Uncharacteristic salinity patterns have resulted in direct mortality, inhibition of reproduction, avoidance of areas, or loss of habitat as described above. The Southern Estuary Fish performance measure (2007) provides the example of red drum (or redfish, *Sciaenops ocellatus*) and other species of sciaenids that rely upon estuarine areas were "abundant at all seasons" during the late 19th Century (Smith, 1896 in performance measure document) but are conspicuously absent from south Biscayne Bay today. Restoration of red drum to the Biscayne Bay failed due in large part to the release (stocking) of juveniles to areas that no longer contained suitable (consistently mesohaline) estuarine environments (Serafy *et al*., 1999; Tringali et al., 2008). Previous studies in Florida Bay (e.g., Ley et al., 1999) and Biscayne Bay (Faunce et al., 2002, Serafy et al., 2003) indicate that mangrove habitats, if restored with the proper salinity gradient, can support high densities of juvenile and adult stages of several economically important fishes, including snappers, grunts, great barracuda, and snook, and even higher densities of their prey (e.g., silversides, killifishes and mojarras).

Lorenz and Serafy (2006; Lorenz et al., 2009) report a higher forage fish abundance in low salinity habitats with more than 40 percent being freshwater affiliates. Rehage and Loftus (2007) speculate that the return of salinity gradients and, in particular, stable oligohaline conditions in the mangrove transition zone should make large portions of the mangrove region suitable for freshwater fish species. They reported that increased freshwater flow in some parts of the mangrove estuaries of northern Florida Bay had resulted in higher abundance and biomass of small-bodied freshwater taxa, and thus some recovery of the demersal forage fish community for piscivorous fishes and wading birds (e.g., roseate spoonbills). Lorenz and Serafy (2006; Lorenz et al., 2009) demonstrated that it took two to three years of low salinity for freshwater forage fish populations to return to a site after lower flows and higher salinities.

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4.1.4 Ecological Implications of Restoring Freshwater Flows to Florida Bay

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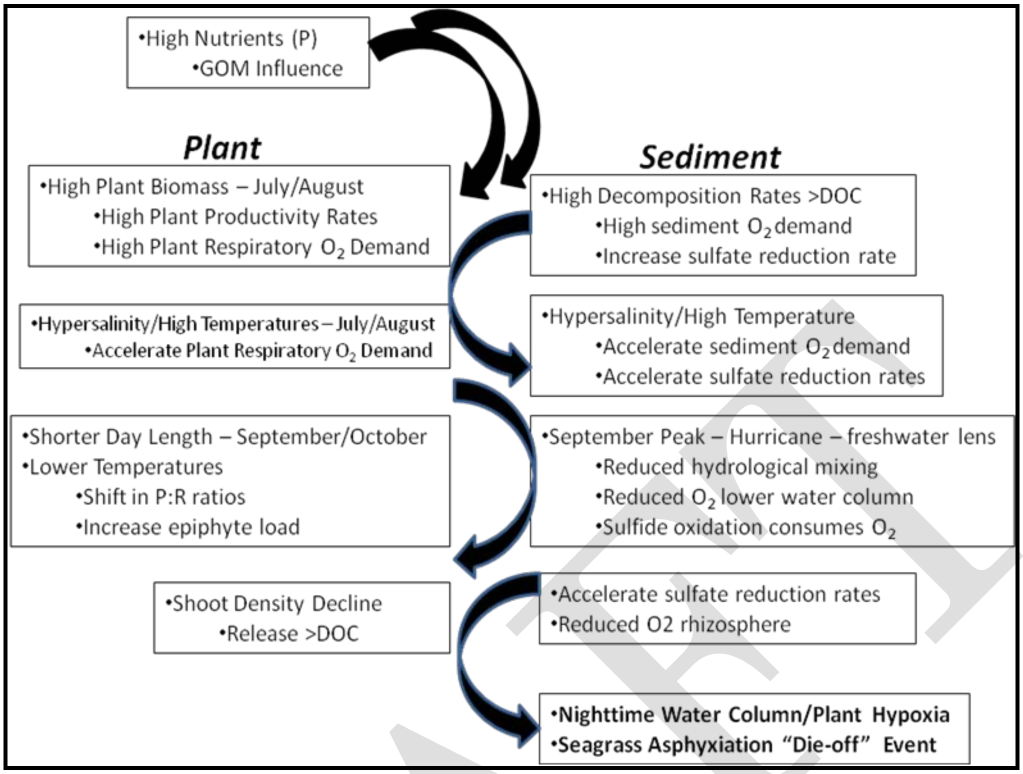
The negative ecological changes observed in Florida Bay in the late 1980s and early 1990s led to concerns about water and natural resource management in south Florida culminating in the Comprehensive Everglades Restoration Plan (CERP). The operational control of freshwater flow has reduced the volume of stored freshwater within the natural system changing hydroperiods and hydropatterns in the marshes and causing the salt/freshwater transition zone to migrate landward into the marshes.

The changes are believed to have contributed to a widespread collapse of the seagrasses in Florida Bay in the fall of 1987. Robblee *et al*. (1991) describe the loss of approximately 10,000 acres (approximately five percent) of the *Thalassia* community and the thinning of approximately 57,000 acres, resulting in impacts of approximately 30 percent of the entire community (Madden *et al*., 2009). The mortality likely resulted from the convergence of multiple environmental stressors (Madden *et al*., 2009) including high summer temperatures, hypersalinity, and high sediment sulfide concentrations combining to reduce productivity and deplete oxygen concentrations in the root zone at the meristem (Madden *et al*., 2009).

Zieman *et al*. (1999, in Madden *et al*., 2009) hypothesize that the collapse occurred after years of quiescent marine/hypersaline conditions that was favorable to the development of the *Thalassia* community producing an excess standing crop that outstripped the resource base and carrying capacity of the community as other stressors occurred. This hypothesis has been supported by continued sporadic losses in high density beds in western Florida Bay (Zieman *et al*., 1999, in Madden *et al*., 2009). Koch *et al.* (2007) noted that the timing of die-off events occurred at the end of the growing season when the plants were down regulating and were not caused directly by the stressors - hypersalinity (<60 practical salinity units [psu]), high temperatures (<33 °C), and porewater sulfide (2-5 mmol L^{-1}). The stressors, however, contribute to plant oxygen (O_2) imbalance in the sediment, from high dissolved organic matter from robust plant growth and phosphorus from the Gulf of Mexico, and in the plants, from the high productivity rates and respiratory demand. They provide a conceptual model of the cascade of stressors leading to a seagrass die-off in western Florida Bay (***Figure 4-2***).



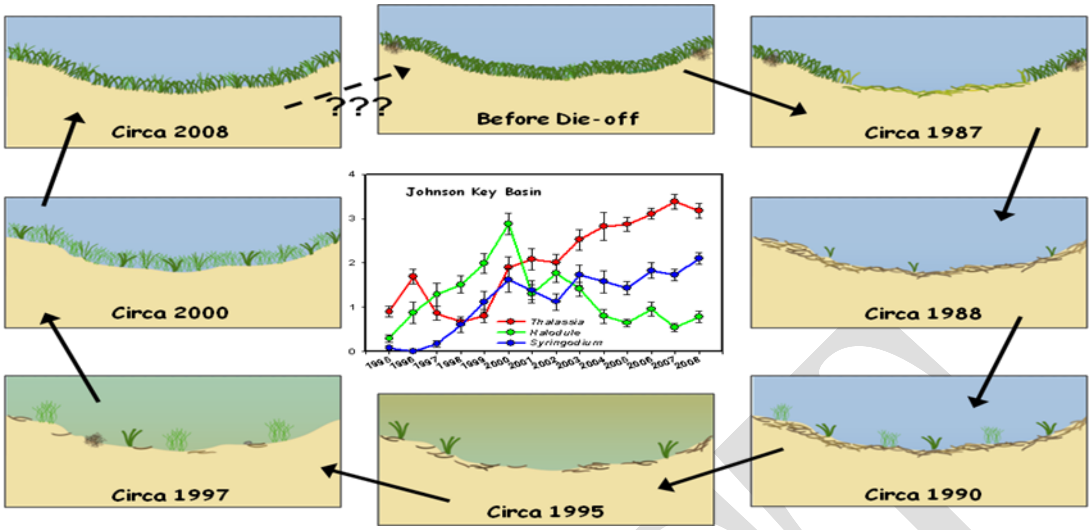
Source: Koch *et al*. 2007

FIGURE 4-2: CONCEPTUAL MODEL OF THE CASCADE OF STRESSORS RESULTING IN A SEAGRASS DIE-OFF IN WESTERN FLORIDA BAY

Key:

GOM	Gulf of Mexico
P	phosphorus
0_2	oxygen
P:R	productivity to respiration ratio
DOC	dissolved organic matter

Hall *et al*. (2009) hypothesize that, if conditions within western Florida Bay do not change, the cycle of seagrass die-off and recovery could be repeating itself based upon Florida Habitat Assessment Program-South Florida monitoring. The caveat is that the monitoring started in 1995, nearly half way into the approximate 20-year cycle; however, the data reveal the pattern of regrowth of a *Thalassia* dominated community in western Florida Bay basins (***Figure 4-33).***



Source: Hall *et al*., 2009

FIGURE 4-3: HYPOTHESIS CONCERNING THE CYCLE OF SEAGRASS LOSS AND RECOVERY IN WESTERN FLORIDA BAY GIVEN CURRENT CONDITIONS

The seagrass losses of 1987 were followed by a cascade of ecological effects in Florida Bay (Madden *et al*., 2009). By 1992, the following had been reported (Madden *et al*., 2009):

- Frequent phytoplankton blooms in central and western Florida Bay (none had been reported from there previously);
- 100 percent mortality of some sponge species;
- 1988 landings of spiny lobster and pink shrimp at Tortugas Banks at their lowest level in decades; and
- Decline in game fish landings.

The phytoplankton blooms have persisted to the present and recently expanded to include eastern Florida Bay (Rudnick *et al*., 2006).

The reduced volume and duration and high variability of flow into the mangrove transition area has stressed submerged aquatic vegetation (SAV) and reduced its spatial and seasonal coverage. The result has been the contraction or elimination of SAV commonly found in brackish or oligohaline habitat (less than 5 psu)--species such as shoal grass, widgeon grass, bladderwort, and southern naiad and fresh macroalgal species including muskgrass (Madden *et al*., 2009). In the SAV performance measure the desired condition in Florida Bay is to recover seagrass beds over most of bay bottom, extending west along the Gulf of Mexico coastal shelf to Lostman's River, and to restore a diverse mosaic of turtle grass, shoal grass, widgeon grass and manatee grass seagrass communities. The desired condition in the Everglades mangrove estuaries is to increase cover and seasonal duration of shoal grass, muskgrass, southern naiad, and bladderwort in coastal lakes and basins.

The technical documentation to support development of minimum flows and levels (SFWMD, 2006) uses widgeon grass as an indicator of SAV habitat and ecosystem status within the transition zone. The technical documentation reported that widgeon grass was sensitive to freshwater inflow, exchanging dominance with muskgrass, southern naiad and bladderwort as conditions became fresher (more oligohaline) and with shoal grass as conditions became greater than 20 psu (more polyhaline). The Miami-Dade Department of Environmental Resources Management (DERM) Fish Habitat Assessment Program (FHAP) sampling of seagrass data in the transition zone showed expansion of the freshwater and brackish water plant assemblages with higher freshwater flows into this zone from the start of data collection in 1995 until the 2005 reporting (DERM, 2005). In a summary of SAV data, Madden *et al*. (2009) found that widgeon grass was absent in this zone during low freshwater inflow periods after 2005.

Summary

Freshwater inflow from the Everglades has been modified through management and differences in the stabilization of salinity have been demonstrated. The changes are believed to have contributed to a widespread collapse of the seagrasses in Florida Bay in the fall of 1987. Because flows into Florida Bay have not consistently changed since the 1987 collapse, the current pattern in the regrowth of seagrass within areas of Florida Bay indicates that the potential exists for a similar collapse event in the future. The restoration of freshwater flows into Florida Bay would benefit and stabilize SAV communities through the range of salinity habitats in the southern Everglades and Florida Bay.

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4.1.5 Endangered Species

The following topic summaries are within the heading "4.1 Landscapes, Key Habitats, and Endangered Species", under the subheading "4.1.5 Endangered Species":

- 4.1.5.1 Snail Kite (*Rosthramus sociabilis plumbeus*)
- 4.1.5.2 Cape Sable Seaside Sparrow (*Ammodramus maritimus mirabilis*)
- 4.1.5.3 Florida Panther (*Puma concolor coryi*)
- 4.1.5.4 Florida Manatee (*Trichechus manatus latirostris*)

4.1.5.1 Snail Kite (*Rosthramus sociabilis plumbeus*)

Author: Kevin Palmer (USFWS)
Contributing reviewers: Terry Rice (Miccosukee Tribe), Heather Tipton (USFWS), Dave Hallac (NPS), Sandra Sneckenberger (USFWS)

Summary
The Everglade snail kite (*Rosthramus sociabilis plumbeus*) is a federally listed endangered species with a south Florida range restricted largely to the wetlands of the Everglades, Lake Okeechobee, Loxahatchee Slough, the Kissimmee Chain of Lakes (KCOL), and the Upper St. Johns River (Martin et al. 2005). The kite population has declined from an estimate of approximately 3400 birds in 1999 to fewer than 700 in 2009. Recent studies implicate low recruitment and a decline in the species' nearly exclusive food source, the apple snail (*Pomocea paludosa)*, as factors in the recent population decline (Cattau et al., 2009, Darby et al. 2005). The existing water management system, especially during extreme meteorological conditions, contributes to unnatural water levels and altered wetland recession rates that are hypothesized causes for the decline in snail kites and their prey.

Demography
Snail kite numbers have declined by more than 75 percent since 1999 (***Figure 4-4***). Two major reductions in numbers occurred following region-wide droughts in 2001 and 2007 (Dreitz et al., 2002; Martin et al., 2007; Cattau et al,. 2009). Recent population estimates are two to three times more accurate than those produced prior to 1997 owing to an improved mark-resighting method first applied in 1997-2000 and refined in 2002 (Dreitz, 2000; Dreitz et al., 2002).

Adult survival has remained fairly constant, around 85 percent with the exception of significant though temporary drops in 2001 and 2007 (***Figure 4-5***). These low adult survival rates, down from estimates prior to these periods, coincide with declines in the overall population (***Figure 4-4***). Adult survival decreased by 16 percent from 2000 to 2002 (Martin et al., 2006), and by approximately 35 percent from 2006 to 2008 (Cattau et al., 2009). Juvenile survival varied widely across years, reaching a record low in 2000 (Cattau et al., 2009). Cattau et al. (2009) concluded that their findings support the hypothesis that increased water level amplitudes in Water Conservation Area (WCA) 3A may play a role in reducing juvenile survival rates. The hypothesis suggests that because kites have been forced, due to ponded water, to initiate nesting at higher ground surface elevations they are more susceptible to receding water levels dropping to points where foraging is difficult or impossible. This in turn would affect fledgling and juvenile survival rates. A preliminary population viability analysis (Martin et al., 2007) predicts very high extinction probabilities in the next 50 years if survival and reproduction rates remain the same as measured from 1997-2005.

Kites disperse when foraging and nesting conditions are unsuitable. Recent data from telemetry indicate that kites can disperse extensively within contiguous wetlands but do not travel readily between widely separated areas such as the WCAs and the KCOL (Cattau et al., 2008).

Habitat

Important breeding areas for kites include the KCOL, Lake Okeechobee, upper St. Johns River, and WCAs. Lake Okeechobee, one of the most productive breeding areas from 1985 to 1995, has produced fewer than 50 fledglings since 1996 with no nesting attempts in the majority of those years (Cattau et al., 2008). Lake stages have been either too high or too low to sustain suitable habitat for kites and snails and the habitat is estimated to have declined by 20,000 acres (60 percent) since 1996 (USFWS, 2007). At the time of this writing, at least four kite nests have been observed on Lake Okeechobee during the 2010 nesting season both in the north and southwest littoral zones.

Kite nesting in WCA 3A, once a productive area, has also declined in recent years (Cattau et al., 2008). Climatic conditions and water management are proposed causes for a reduction in habitat suitability for both nesting kites and apple snails. Recent modeling of hydrologic and snail kite demographic variables in WCA 3A found a statistically significant negative effect of rapid recession rates on nest success and fledgling survival (Cattau et al., 2008). Additionally, low water levels during the nesting season correlate with reduced nest success and fledgling survival (Cattau et al., 2008).

Ponding in southern WCA 3A has degraded wet prairie habitat necessary for kite foraging and apple snail reproduction (Darby et al., 2005; Powers, 2005; Cattau et al., 2008; Zweig and Kitchens, 2008). Zweig and Kitchens (2008) found that prolonged high water levels were associated with the loss of emergent wet-prairie species such as *Eleocharis elongata*, *Panicum hemitomon*, *Panicum geminatum*, and *Utricularia* spp., and that vegetation shifts can take place within as few as four years. Wet prairie emergents were replaced by *Nymphaea odorata*, which provides less suitable habitat for apple snails and consequently the kite (Karunaratne et al., 2006). Since the loss of Lake Okeechobee and WCA 3A as productive kite nesting habitat, the KCOL has become an important nesting area for kites supporting 80 percent of all active nests in 2009 (Cattau et al., 2009).

Apple Snail

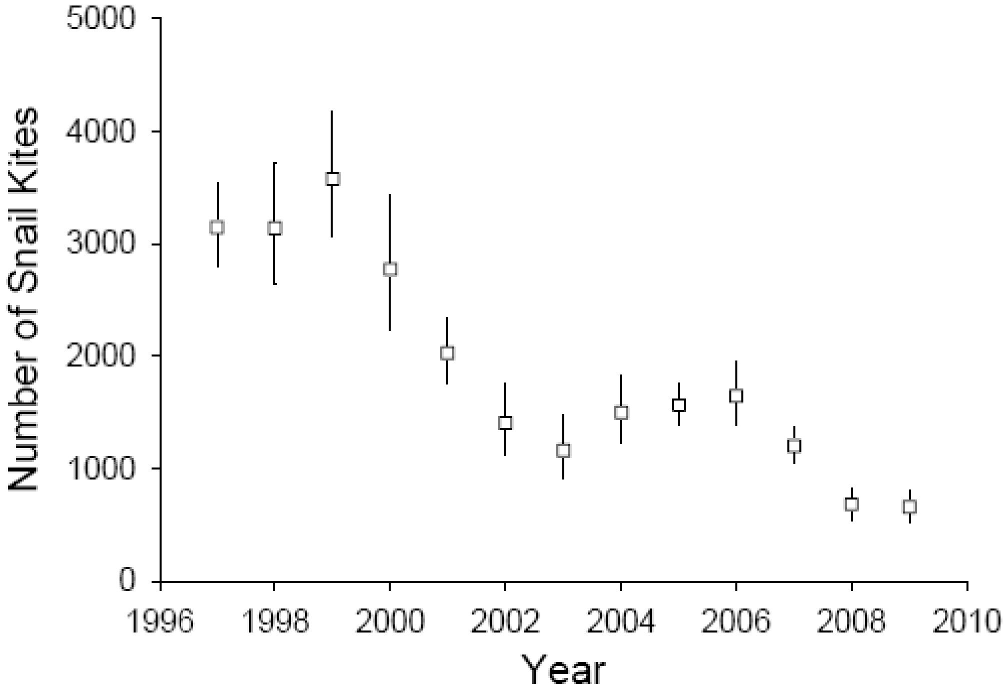
Using field data from 1995 to 2004, Darby et al. (2006) estimated that snail densities less than 0.14 individuals per square meter are unable to support kite foraging. Darby et al. (2008) reported that adult apple snails can survive dry downs lasting up to 12 weeks in the lab, although smaller snails survive at lower rates (less than 50percent alive after eight dry weeks). Apple snail recruitment may be truncated if dry downs occur during the peak breeding season when young snails can become stranded, or when water levels drop below approximately 10 centimeters at which point apple snails stop moving, and thus reproducing (Darby et al., 2008). Darby et al. (2005) reported that relatively high water (above approximately 40-60 centimeters) also negatively impact apple snail egg cluster production by delaying the peak of egg laying, and decreasing the number of eggs produced per snail. Declines in recruitment can be caused by low or high water during the breeding season and result in decreased snail densities the following year. Based on these combined results, Darby et al. (2009) recommended a range of water depths of approximately 10-50 centimeters during the peak apple snail breeding period (April-June).

Threats

Additional threats to kites include altered marsh vegetation resulting from eutrophication (Havens and Gawlik, 2005). Invasive vegetation such as water hyacinth and cattail can degrade habitat by forming dense growths that hinder snail kite foraging and are unsuitable for apple snails. Areas of dense sawgrass resulting from altered hydrology can also effect habitat suitability for kites and apple snails (Rutchey et al., 2005; Bennetts et al., 2006). Habitat loss and fragmentation are also factors influencing survival during droughts, despite the species' dispersal ability (Martin et al., 2006). Copper, used in fungicide applications and commonly found in disturbed areas of Everglades wetlands, bioaccumulate in apple snails and may lead to birth defects in snail kite nestlings (Frakes et al., 2008). Kites, limpkins (*Aramus guarauna*), and other predators have been observed eating the exotic island apple snail (*Pomacea insularum*). Juvenile snail kites have difficulty handling mature exotic snails and experienced significantly lower net daily energy balances when feeding on exotic snails (Cattau et al., 2010).

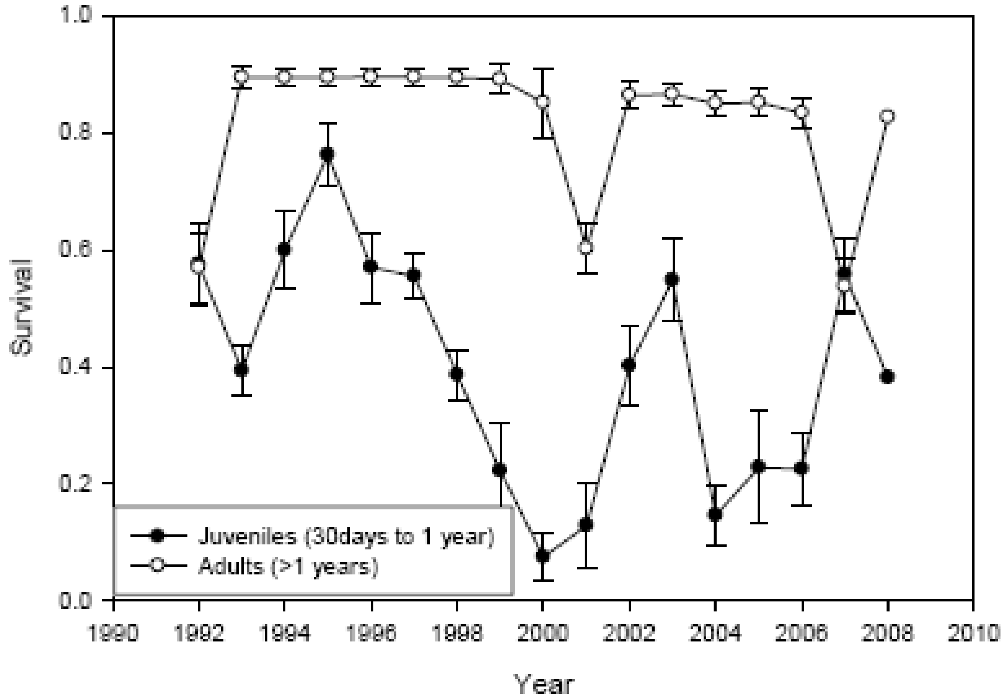
Conservation

An independent scientific review of multi-species avian conservation research offered recommendations for the conservation of the Everglade snail kite, especially in the important breeding area of WCA 3A. The expert panel recommended that "water management should maintain lower water levels during the fall/winter months (September-December) to mitigate effects of longer hydroperiod and deeper water on vegetation, and should maintain higher water levels during the spring/summer (March-July) to provide for better conditions during the snail kite breeding season. These requirements should be formally entered into the Army Corps of Engineers (USACE) System-wide Operations Manual due for revision in 2010" (Sustainable Ecosystems Institute, 2007, page 13).



Source: Cattau et al., 2009
Note: Error bars correspond to 95 percent confidence intervals

FIGURE 4-4: ESTIMATED SNAIL KITE POPULATION SIZE FROM 1997 TO 2009



Source: Cattau et al. 2009
Note; Error bars correspond to 95% confidence intervals, which cannot be estimated for 2009 estimates until data from the 2010 survey season are acquired.

FIGURE 4-5: MODEL-AVERAGED ESTIMATES OF ADULT (WHITE CIRCLES) AND JUVENILE (BLACK CIRCLES) SURVIVAL FROM 1992 TO 2008

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4.1.5.2 Cape Sable Seaside Sparrow (*Ammodramus maritimus mirabilis*)

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Summary

The Cape Sable seaside sparrow (*Ammodramus maritimus mirabilis*) is a federally listed endangered species endemic to the seasonally dry marl prairies of south Florida's Everglades. They are located within six distinct subpopulations that occur almost exclusively within Everglades National Park. The depth, duration and timing of seasonal water levels within the sparrow's habitat have a significant impact on the breeding success of sparrows (Baiser et al., 2008; Lockwood et al., 1997; 2001; 2003; Pimm et al., 2002). A number of studies have been conducted within the last ten years to develop a more accurate understanding of how hydrology affects sparrow habitat and demography.

Population

The six distinct subpopulations of the Cable Sable seaside sparrow are designated A through F (***Figure 4-6***). Population estimates employ extensive range-wide surveys to census singing males during the nesting season, with a statistically-derived multiplier of 16 birds per documented male (Kushlan and Bass, 1983; Walters et al., 2000; Pimm et al., 2002). Between 1992 and 1993, the population declined from an estimate of 6,576 birds to 3,312 (***Figure 4-7***). Since then, the total population has remained relatively constant while the number of birds in each of the subpopulations has fluctuated.

Subpopulations A, C, D and F are the smallest in terms of number of sparrows and area with the exception of A which has a large amount of available habitat. Subpopulations D and F have come close to extirpation, with recent surveys detecting few or no sparrows (Boulton et al., 2009; Slater et al., 2009). During the 2006-2008 nesting seasons, intensive ground surveys were conducted in subpopulations C, D, and F to better understand these small subpopulations (Lockwood et al., 2006; Boulton et al., 2009). Data collected in these surveys included territory size, fecundity, nest success and survival rates. Results indicate that the small subpopulations exhibit: (1) suppressed breeding, (2) an excess of single males, (3) nest survival comparable to larger subpopulations, (4) low hatch rate, and (5) larger territory sizes than birds in the larger subpopulations. Boulton et al. (2009) concluded that the small subpopulations are demographically dynamic and subject to the negative effects of low densities (e.g., Allee effects). In addition to C and D, subpopulation A was intensively surveyed for the first time in 2009 and positive results were reported for this imperiled subpopulation (Virzi et al., 2009). A promising 19 breeding pairs were detected in subpopulation A and the subpopulation exhibited similar traits to the larger subpopulations like the presence of few unmated males and comparable clutch sizes, adult return rates, and proportion of early to late nests (Virzi et al., 2009). The subpopulation was reported as extant and functional.

Scientists have been banding sparrows since 1994 with the greatest effort concentrated in the larger subpopulations (B and E). During the period 1994-2005, only four instances of long-range sparrow movement between subpopulations A, B and E were documented (Lockwood et al., 2007). Since the intensive surveys began in 2006, movements have been documented between four subpopulations. This included two single males from subpopulations D and F that moved to subpopulation C, and a male that migrated 31.0 kilometers from subpopulation F to B (Lockwood et al., 2006, 2007; Van Houtan et al., 2010).

Habitat

Lockwood et al. (2005) and La Puma et al. (2007) investigated the effects of fire on sparrows. They hypothesized that fire was not necessary to maintaining suitable habitat for sparrows, as had been assumed previously. Sparrow density and nest success were measured for four years in a post-burn plot previously occupied by sparrows. Sparrows re-colonized the plot within three to four years, but their density and nest success did not exceed pre-burn levels, contrary to what would be expected if fire enhanced sparrow habitat (La Puma et al., 2007). Low water elevations during the early breeding season may increase the risk or intensity of fires, which can kill adult sparrows and/or render the sparrow habitat unsuitable for up to three years. Prolonged inundation of habitat post-burn can lengthen the recovery interval of the habitat by as much as seven years (Sah et al., 2008).

Baiser et al. (2008) confirmed earlier findings by Boulton et al. (2007) that nesting success declines later in the breeding season due to rising water levels and increased predation. Rice rats (*Oryzomys palustris*) and water moccasins (*Agkistrodon piscivorus*) appear to be the sparrow's main predators, taking eggs, nestlings, and adults. Baiser et al. (2008) noted that in the nests they monitored, 97 percent of nest failure was the result of predation.

Sparrows build their nests 14 centimeters, on average, above ground surface and often walk along the ground to forage. Water levels that rise above ground surface during the nesting season (March through July), may disrupt breeding and can destroy nests and drown nestlings (Lockwood et al., 2001). Long hydroperiods (greater than 210 days) over several years would change the vegetative character of the habitat from marl prairie to freshwater marsh and eliminate use of this habitat by the sparrow (Pimm et al., 2002; Sah et al., 2008). Alteration of the natural hydrology, from construction of the Central and South Florida Project, remains the largest threat to the Cape Sable seaside sparrow and is the focus of ongoing restoration planning.

Additional Threats

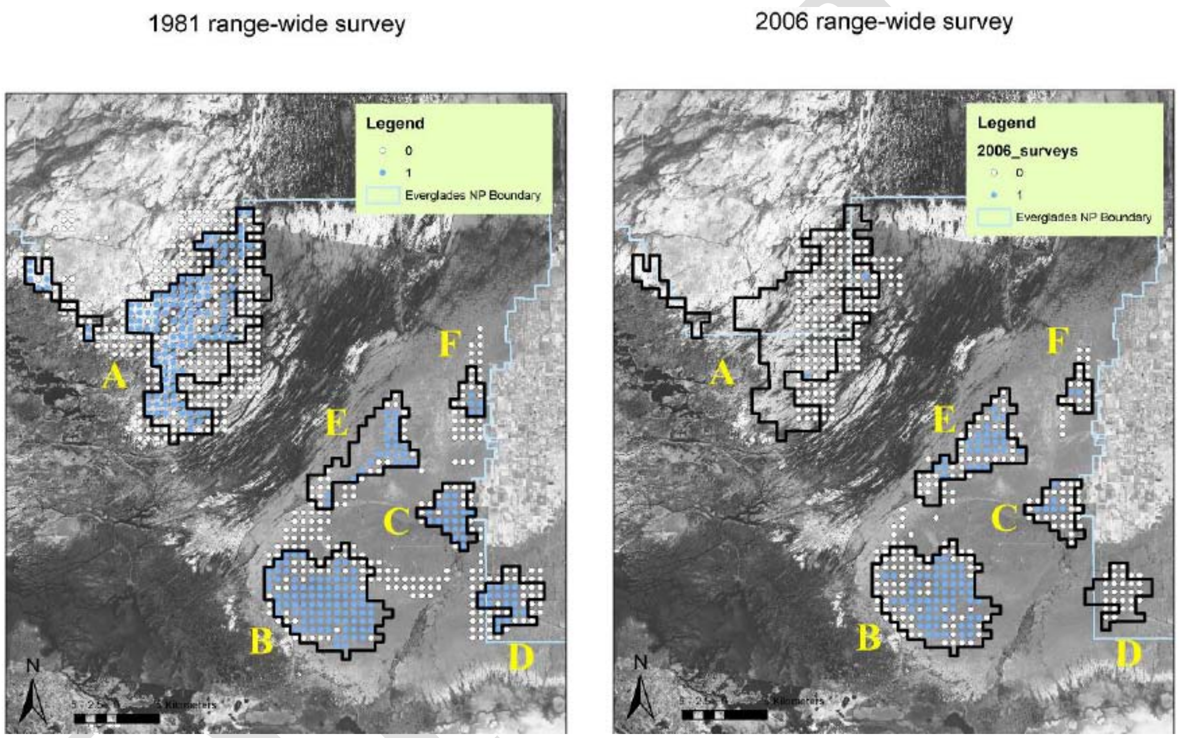
The recent establishment of the non-native Burmese python (*Python molurus bivittatus*) in Everglades wetlands may harm sparrows, as pythons inhabit the same areas as sparrows and are known to eat birds of similar size (Snow et al., 2007; Slater et al., 2009). Natural and man-made fires could have catastrophic effects on sparrow populations if they consume large areas of sparrow habitat. This is of most concern for the drier eastern subpopulations that lie close to the urban interface (Lockwood et al., 2001). Finally, sea level rise poses a threat for this species, which inhabits low lying areas close to the coast.

Conservation

The U.S. Fish and Wildlife Service (USFWS) has recently revised the designation of critical habitat for the Cape Sable seaside sparrow (see 72 FR 62736). The final rule reduced the total acreage of critical habitat to 84,865 acres contained within five units that include portions of subpopulations B through F. The final designation delineates specific areas suitable for sparrows and defines four primary constituent elements essential to the conservation of the species: (1)

calcitic marl soils; (2) herbaceous vegetation that includes greater than 15 percent combined cover of live and standing dead vegetation; (3) contiguous open habitat; and (4) a suitable hydrologic regime.

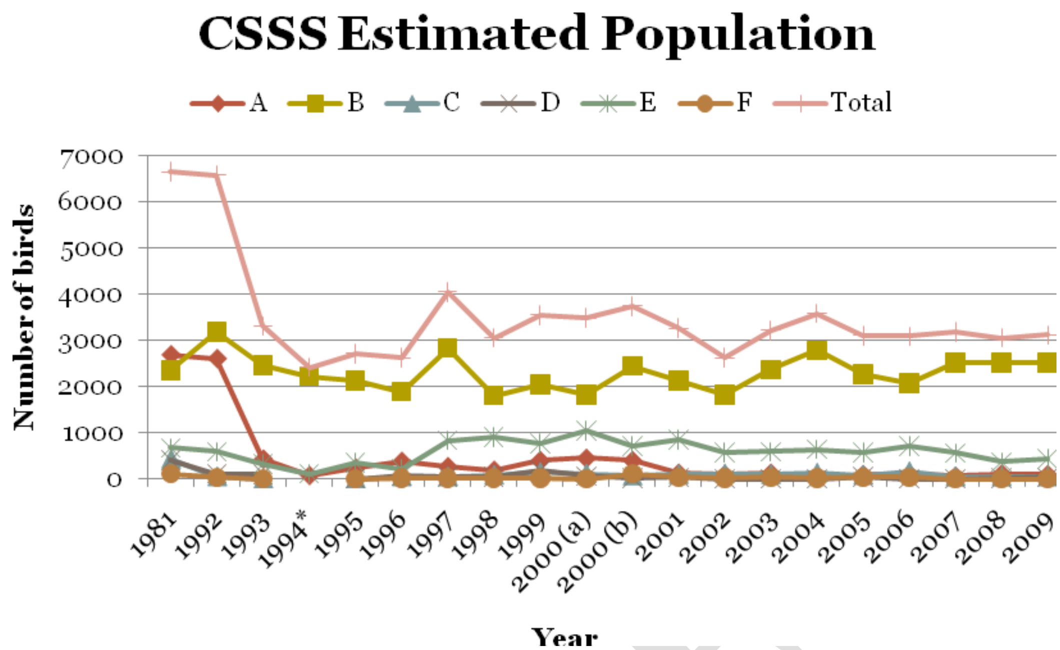
An independent scientific review of multi-species avian conservation (Sustainable Ecosystems Institute, 2007) offered recommendations for the short and long-term conservation of the sparrow. These recommendations included restoring hydrologic conditions on the marl prairies, exploring methods to reduce predation, continuing intensive monitoring of each subpopulation, researching conspecific attraction techniques, and improving communication and coordination with various research groups and government agencies.



Source: Cassey et al. 2007; Slater et al. 2009

Note: Survey points have been converted to illustrate sparrow presence (blue) or absence (white) within the four management units

FIGURE 4-6: CAPE SABLE SEASIDE SPARROW (*AMMODRAMUS MARITIMUS MIRABILIS*) DISTRIBUTION FROM THE FIRST RANGE-WIDE SURVEY CONDUCTED DURING 1981 AND THE 2006 SURVEY



Source: USFWS graphic using survey data reported by ENP
Note: numbers estimated from range-wide surveys in 1981 and 1992-2009

FIGURE 4-7: CAPE SABLE SEASIDE SPARROW (*AMMODRAMUS MARITIMUS MIRABILIS*) TOTAL AND SUBPOPULATION (A-F)

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4.1.5.3 Florida Panther (*Puma concolor coryi*)

Author: Marilyn Stoll (USFWS)
Contributing reviewer(s): Chris Belden (USFWS), Darrell Land (FWC), Dave Oronato (FWC)

Summary
Florida panther demographic and population trends have improved since initiation of a genetic restoration program in 1995. Trends in quality, quantity, pattern, and distribution of habitat in landscapes used by panthers continue to decline primarily as a result of human development and population growth. Climate change impacts would likely increase competition between human and panther populations for space in the Everglades eco-region, and may also affect the potential to establish panther populations (required for recovery) outside south Florida.

Population
Genetic restoration improved trends in several demographic parameters for the only remaining breeding population of panthers, which is sustained by the Everglades eco-region[20]. The documented panther population increased from approximately 62 in 2000 to 117 in 2007 (McBride et al., 2008),[21] the period of time since completion of the initial Everglades Restoration Plan. Before genetic restoration, the estimated population increased gradually from a low of 12 to 20 panthers in the early 1970s (USFWS, 2008) to 30 to 50 panthers in 1994 (USFWS, 1994). Increased male dispersal out of south Florida has coincided with the increase in panther numbers and population density (Maehr et al., 2002). Isolation from other populations and habitat loss continue to be a conservation challenge.

Habitat
Habitat loss, degradation, and fragmentation continue to threaten panther conservation and recovery. Panthers require large scale habitat mosaics for breeding, hunting, and cover. To date, most habitat selection studies have revealed that panthers generally select forest habitats and use other natural habitats in proportion to their relative availability (Cox et al., 2006; Kautz et al., 2006; Land et al., 2008). Since panthers, in general, avoid developed areas, increasing human development and population growth exacerbate habitat loss and population isolation (Kautz et al., 2006; Hostetler et al., 2009).

Threats
Urbanization, residential development, road construction, and conversion of habitats to agriculture, mining, and mineral exploration continue to adversely alter potential panther habitat throughout the Everglades ecosystem and the Southeast (USFWS, 2008). Land use change over a ten-year period is shown in ***Table 4-1*** for three panther zones identified by Kautz et al. (2006) within the Everglades ecosystem (***Figure 4-8).***

[20] Genetic restoration success is indicated by increased kitten survival, decreased adult female mortality (Pimm et al., 2006), recolonization of recently occupied areas, (McBride et al., 2008), and increased genetic health (Service, 2008). The occurrence of other characteristics attributed to inbreeding (Roelke et al., 1993) have been sharply reduced (crooked tails and cowlicks, Land et al., 2004; undescended testicles, Mansfield and Land 2002; congenital heart defects, Service, 2008). Genetic restoration effects on reproductive parameters such as low sperm quality and immune deficiencies have not been evaluated. Two introgressed panthers had higher sperm quality than uncrossed panthers (Service, 2008).

[21] The documented panther population is based on extensive efforts to count all live panthers (excluding kittens in dens) known from credible physical evidence (McBride et al., 2008). Beier et al. (2003) found population estimates from radio-collared panther studies (Maehr et al., 1991) could not be extrapolated to areas with unknown panther densities.

Approximately 11,000 square miles (7 million acres) of Florida agricultural lands, native habitat, and lands considered for conservation purchase or within one mile of conservation lands are predicted to be converted to urban uses by 2060 (Zwick and Carr, 2006).[22] ***Figure 4-9*** illustrates the projected expansion of the human population in south Florida into areas of undeveloped land that currently or potentially supports panthers (Zwick and Carr ,2006).

The absence of documented female panther dispersal to the north of the Caloosahatchee River currently limits the breeding population to the confines of southern Florida (USFWS, 2008). Projected expansion of the human population in Florida (***Figure 4-9,*** Zwick and Carr, 2006) and conversion of forests in the southeastern United States (Wear and Greis, 2002) would affect the availability of habitat for panther recolonization or reintroduction in the future.

Management and Conservation

Federal listing under the Endangered Species Act (ESA) of 1973, as amended (ESA; 16 U.S.C. 1531 *et seq.*), provides protection to both panthers and the ecosystems on which they depend. Kautz et al. (2006) identified landscapes occupied by panthers (Primary Zone), adjacent areas that, with some restoration, might support an expanding population (Secondary Zone), and areas panthers could use to disperse north of the Caloosahatchee River (Dispersal Zone) (***Figure 4-8).*** Federal land management, regulatory, funding, and consulting agencies now use these zones to support analyses and decision processes for panthers pursuant to the ESA (USFWS, 2008).

The U.S. Fish and Wildlife Service (USFWS) (2007) in cooperation with the National Park Service and the Florida Fish and Wildlife Conservation Commission (FWC), created the *Interagency Florida Panther Response Plan* to effectively manage human-panther interactions. The *Response Plan* also includes a proactive panther education and outreach strategy.

Other Knowledge Gained

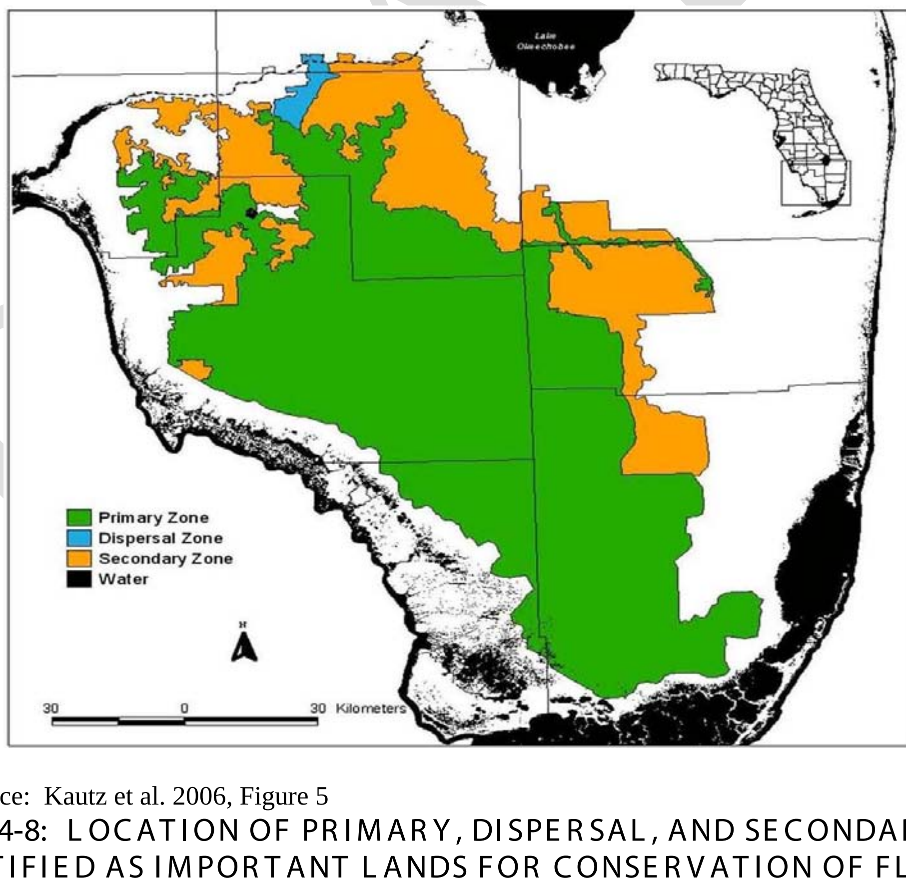
Competition between human and panther populations for space in the Everglades eco-region would likely increase due to impacts associated with climate change. Climate change impacts might also affect the potential to establish panther populations (required for recovery) outside of south Florida. Predicted or possible climate change impacts which may directly affect panthers include shifts in terrestrial-aquatic and fresh-saltwater habitats and species assemblages; degraded terrestrial habitats, disruption of natural system food webs, reduced natural system resistance to and increased recovery time from hurricanes, droughts, floods, fires, invasive species, and diseases, and increased bacterial processes and nutrient cycling (SFWMD, 2009).

[22] Zwick and Carr (2006) based land use predictions on projected human population growth. The top 5 of 67 Florida counties predicted to undergo the greatest transformations are in south-central Florida; Glades and Hardee Counties were predicted to have 14 times more urban development in 2060. The projected population exceeded available vacant lands in Lee and Collier Counties and was allowed to spill over into adjacent areas resulting in a continuous urban strip from Ft. Meyers to West Palm Beach.

TABLE 4-1: ACRES OF 1995 AND 2004 LAND USE/LAND COVER TYPES WITHIN PANTHER PRIMARY, SECONDARY, AND DISPERSAL ZONES, AND CHANGE FROM 1995 TO 2004 IN ACRES (AC) AND PERCENT (%)

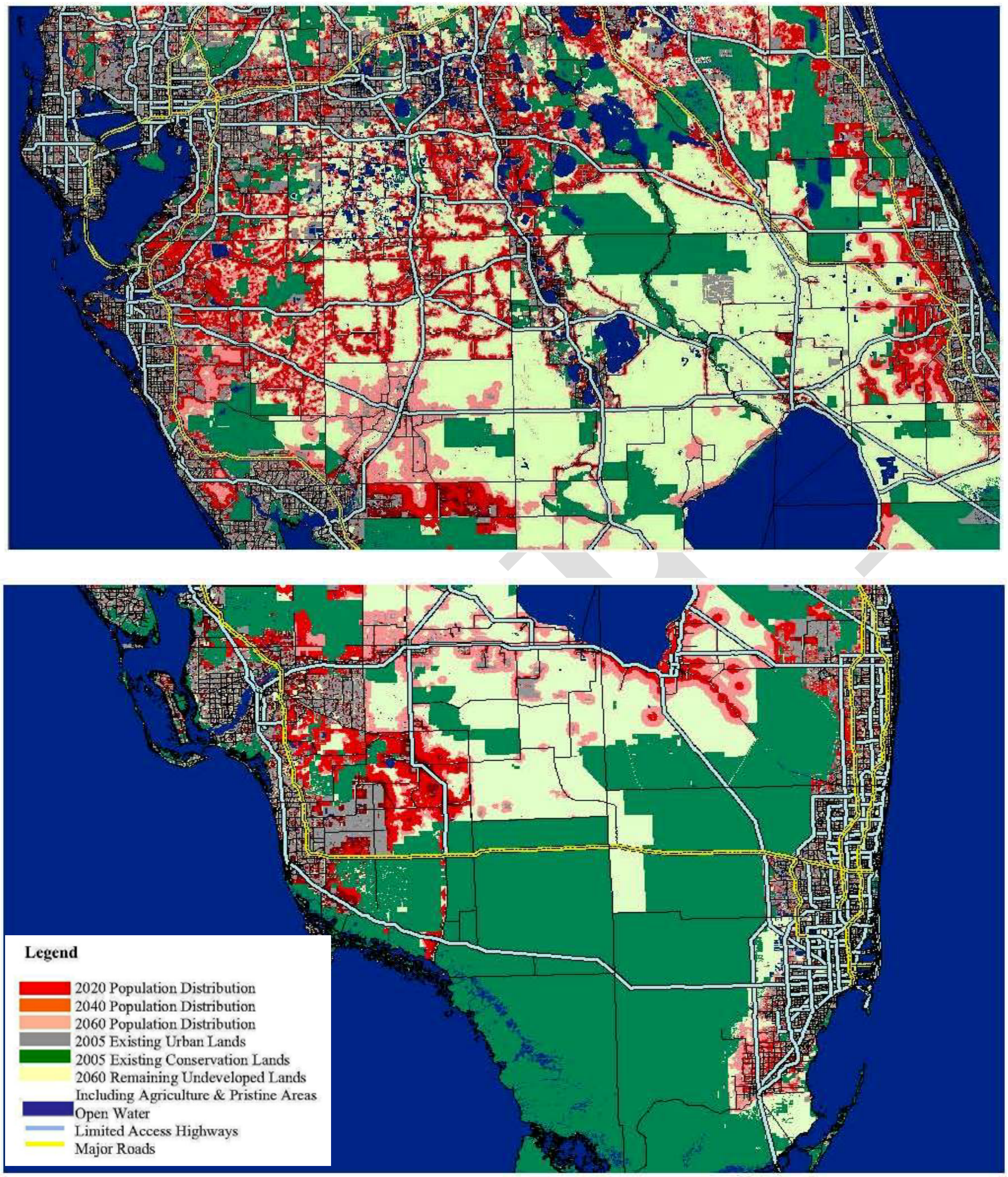
	Primary zone (ac)			Dispersal zone(ac)			Secondary zone (ac)			Total panther zones(ac)		
Land cover type	**1995**	**2004**	**+/- %**	**1995**	**2004**	**+/- %**	**1995**	**2004**	**+/- %**	**1995**	**2004**	**+/- %**
Wetland forest	865,606	842,753	-2.6	4,626	4,269	-7.7	46,057	42,598	-7.5	916,289	889,620	-2.9
Upland forest	161,042	97,117	-39.7	3,558	940	-73.6	41,967	29,861	-28.8	206,568	127,919	-38.1
Freshwater marsh	925,034	984,705	6.5	2,086	3,428	64.4	347,556	355,604	2.3	1,274,653	1,343,737	5.4
Prairie and shrub lands	58,199	111,503	91.6	2,451	5,918	141.4	49,823	79,341	59.2	110,471	196,762	78.1
Agriculture	173,353	165,201	-4.7	13,657	12,775	-6.5	294,719	282,982	-4.0	481,729	460,959	-4.3
Barren, urban, exotics	37,648	22,218	-41.0	1,423	351	-75.3	26,845	13,572	-49.4	65,914	36,142	-45.2
Coastal wetlands	43,168	35,385	-18.0	0	0	0.0	44	0	-100.0	43,213	35,385	-18.1
Aquatic	6,538	11,736	79.5	84	200	137.9	5,095	8,155	60.1	11,717	20,091	71.5
Total area	**2,270,590**	**2,270,618**		**27,885**	**27,882**		**812,107**	**812,114**		**3,110,554**	**3,110,614**	

Note: GIS data for 2004 (USFWS) is compared with Kautz et al. 2006, Table 3 (1995 data converted from hectares to acres).



Source: Kautz et al. 2006, Figure 5

FIGURE 4-8: LOCATION OF PRIMARY, DISPERSAL, AND SECONDARY ZONES IDENTIFIED AS IMPORTANT LANDS FOR CONSERVATION OF FLORIDA PANTHER HABITAT



Source: (Zwick and Carr 2006, Figures 6 and 7)

Note: Illustrates the predicted expansion of the human population into areas currently or potentially used by panthers (Zwick and Carr 2006, Figures 6 and 7).

FIGURE 4-9: PROJECTED HUMAN POPULATION DISTRIBUTION FOR 2020, 2040, AND 2060 IN SOUTH FLORIDA

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4.1.5.4 Florida Manatee (*Trichechus manatus latirostris*)

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The Florida manatee is native to Florida with a long life span (approximately 60 years), is relatively old at maturity (four-seven years), has a low reproductive rate (one calf every three years, with an 11-13 month gestation), and high parental investment (two-year calf dependency). The manatee's physiology (an extremely low metabolic rate coupled with a high thermal conductance) limits its ability to thermoregulate in cold waters and makes it susceptible to cold-related stress and death (FWC, 2007). The creation of warmwater outfalls from electric power generating plants and other industrial facilities over the past 50 years has probably contributed to manatee population growth by providing access to more warmwater refugia during winter and by reducing the extent of cold-related mortality (FWC, 2007).

The most recently published information on Florida manatee population demographics (growth, survival, and reproductive rates) includes studies by Craig and Reynolds (2004), Kendall et al. (2004), Langtimm et al. (2004), and Runge et al. (2004). All of these analyses indicate that, with the exception of the Southwest region of the state, manatees are increasing or stable throughout Florida. [Note - The southwest region was the most data-poor of all the management units when these studies were conducted.] While these analyses used models that shared many of the same parameters, federal and state scientists and managers expressed a desire to have a single, common modeling framework to form the basis of future status reviews.

Runge et al. (2007a) developed a stochastic, stage-based population model that integrates the known life-history parameters of the manatee and combines this information with projections of future threats, such as reduction in warmwater capacity because of power plant closures. The primary function of the core biological model (CBM) is to forecast relative population size, growth rates, and quasi-extinction risk of manatees in these four geographic regions for 50 to 150 years: Atlantic, Southwest, Upper St. Johns and Northwest (***Figure 4-10***).

According to Runge et al. (2007a), the state-wide population is projected to increase slowly for 10-15 years, then decline as the loss of warmwater capacity limits the manatee population. In the northwest and upper St. Johns regions, the CBM predicts that manatee populations would increase over time until warmwater capacity is reached, at which point growth would taper off. In the Atlantic region, the model predicts a stable or slightly increasing population over the next decade or so, and then a decrease as industrial warmwater capacity is lost. In the Southwest region, the model predicts a decline over time, driven by high annual mortality in the short-term and exacerbated by loss of industrial warmwater refuges over the next 40 years.

Runge et al. (2007b) applied the CBM to analyze the effects of the following five threats on the manatee population: (1) watercraft-related mortality, (2) loss of warm water habitat in winter (3) mortality from water-control structures, (4) entanglement, and (5) red tide. The model essentially expresses the contribution of each threat as it affects manatee persistence, by removing them, one at a time, and comparing the results to the "status quo" scenario. Status quo represents the population status in the continued presence of *all* of the threats, including the threat of the potential loss of warm water in the future due to power plant closures and the loss of springs and/or reduction in spring flows.

This quantitative analysis calculated probabilities associated with three possible levels of quasi-extinction (100, 250, and 500 adult manatees); three time frames (50, 100, and 150 years); and six different threats (collisions with boats, hypothermia from the loss of warmwater sources, drowning or crushing in water control structures, poisoning from red tide, drowning due to entanglement as well as combining watercraft collisions with loss of warm water).

Using a minimum population count of 3,300 manatees, Runge et al. (2007b) estimated the probability of the manatee population falling to less than 250 adults on either the Atlantic or Gulf coasts within 100 years is 8.6 percent. Complete removal of the warmwater threat alone would reduce this risk to 4.2 percent; complete removal of the watercraft threat to 0.4 percent; removal of both threats would reduce the risk to 0.1 percent (***Figure 4-11***). Over the long term, the expectation is that the manatee population would stabilize at a lower level. The probability of outright extinction is low, but the probability of a significant decline is high.

Under the Endangered Species Act (ESA), the definition of an endangered species is one that is in danger of extinction throughout all or a significant portion of its range. In contrast, the definition of a threatened species is one which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range. Presently, Florida manatees are exhibiting positive growth, good reproductive rates, and high adult survival throughout the state. As of January 2010, the abundance of manatees is at least 5,000 animals with all four management units in Florida exhibiting increasing rates of growth. Based on the CBM results, the USFWS believes the Florida manatee no longer meets the definition of an endangered species and should be reclassified as threatened (USFWS, 2007).

With the emergence of the Comprehensive Everglades Restoration Plan (CERP) and the requisite modifications to the Central and Southern Florida (C&SF) project, the USFWS (along with several federal and state agencies including Miami-Dade County formed the CERP Interagency Manatee Task Force), recognized the opportunity to minimize and even eliminate manatees from accessing many of the canals that interconnect throughout south Florida. Typically, once manatees enter the C&SF system they become entrapped and are at risk from the lack of sufficient forage, cold water temperatures, and structure-related injury and mortality.

The Task Force submitted a plan to the USACE and South Florida Water Management District (SFWMD) recommending, among several protection measures, the installation of barriers along the south side of Lake Okeechobee to prevent manatees from entering the Everglades Agricultural Area (EAA). In December 2006, seven barriers were installed at three gate openings, thereby preventing manatees from accessing 178 miles of canals in the EAA.

In Runge et al.'s (2007b) assessment of threats to the manatee population, the probability is 4.34 percent that the adult population would fall below 250 animals on either coast within 100 years when the threat due to water control structures is removed state-wide. Though not modeled, the placement of the barriers reduces the risk to manatees by blocking access through these water control structures and eliminates or minimizes potential manatee conflicts during implementation of nine CERP projects proposed for construction downstream.

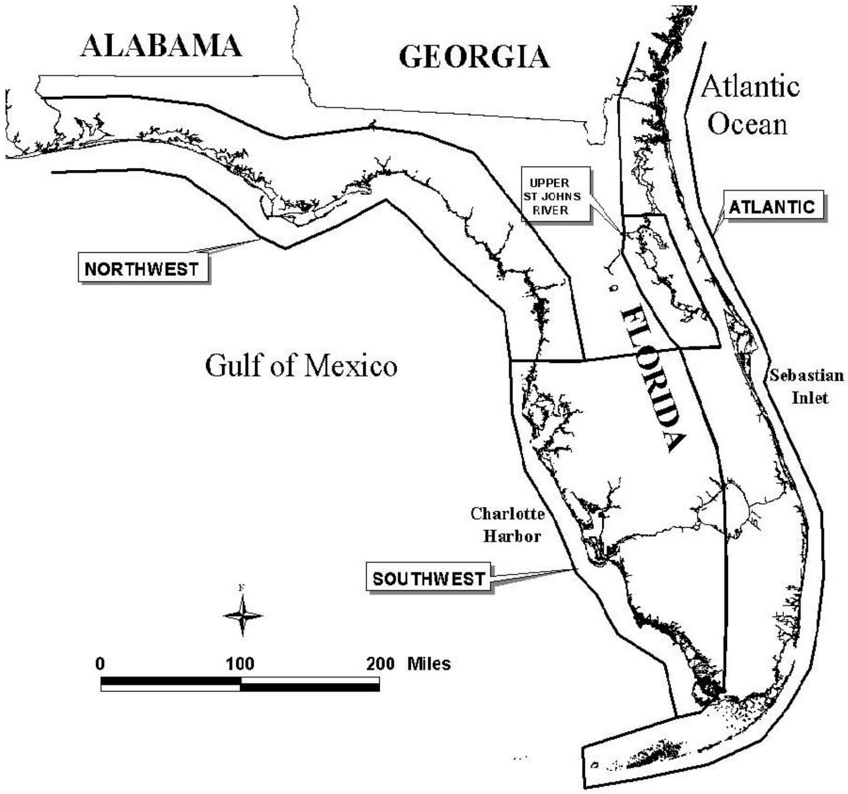

FIGURE 4-10: FLORIDA MANATEE DISTRIBUTION WITHIN THE FOUR DESIGNATED REGIONAL MANAGEMENT UNITS

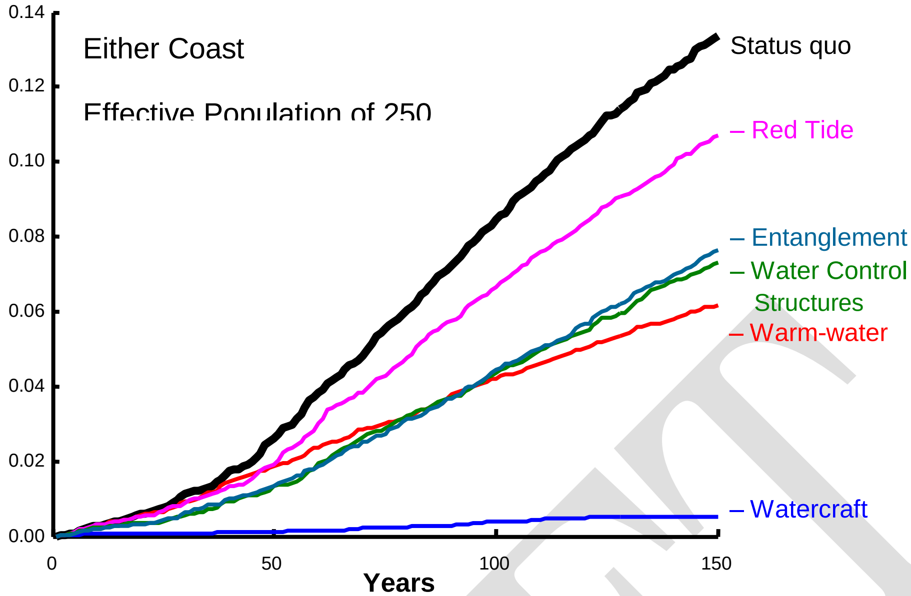

FIGURE 4-11: PROBABILITY OF THE ADULT (EFFECTIVE) POPULATION FALLING BELOW A THRESHOLD OF 250 ON EITHER THE ATLANTIC OR GULF COAST AS A FUNCTION OF YEARS FROM PRESENT FOR SIX THREAT SCENARIOS (REMOVAL OF EACH OF THE THREATS)

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4.2 Indicators of Restoration Success

The following topic summaries are under the heading “4.2 Indicators of Restoration Success”:

- 4.2.1 Comprehensive Everglades Restoration Plan Key Species
  - 4.2.1.1 Alligators (*Alligator mississippiensis*)
  - 4.2.1.2 Wading Birds
  - 4.2.1.3 Oysters (*Crassostrea virginica*)
  - 4.2.1.4 Prey Fish
- 4.2.2 Comprehensive Everglades Restoration Plan Module-specific Ecological Indicators
  - 4.2.2.1 Lake Okeechobee
  - 4.2.2.2 Northern Estuaries
  - 4.2.2.3 Greater Everglades
  - 4.2.2.4 Southern Coastal Systems

4.2.1 Comprehensive Everglades Restoration Plan Key Species

The following topic summaries are under the heading “4.2.1 CERP Key Species”:

- 4.2.1.1 Alligators (*Alligator mississippiensis*)
- 4.2.1.2 Wading Birds
- 4.2.1.3 Oysters (*Crassostrea virginica*)
- 4.2.1.4 Prey Fish

4.2.1.1 Alligators (*Alligator mississippiensis*)

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Introduction

Alligators are one of the key species used by the Comprehensive Everglades Restoration Plan (CERP) Monitoring and Assessment Plan (MAP) to assess the health of the Everglades ecosystem as restoration progresses. The majority of alligator monitoring and research in the Everglades that has taken place over the past decade has been conducted by the CERP MAP. The MAP examines alligator body condition and population density in relation to water depth patterns, salinity, and prey abundance (RECOVER, 2009a), all of which have been altered by compartmentalization and disrupted sheet flow in the Greater Everglades (RECOVER, 2009b). Results from 2006 to 2008 MAP monitoring indicate that both densities and body condition of alligators were below restoration targets across the system, except in Arthur R. Marshall Loxahatchee National Wildlife Refuge (LNWR) (during a period when inundation occurred over multiple consecutive years) where relative densities remained high (RECOVER, 2009b). MAP restoration targets for both density and body condition are based on the upper 4th quartile of the distribution of values from all survey routes for the 1999 to 2006 period of record (RECOVER, 2009b).

Relative Density

Alligators are counted via surveys along routes in LNWR, the Water Conservation Areas (WCA), Everglades National Park (ENP), and eastern Big Cypress National Preserve. Relative density is the total number of non-hatchling animals encountered on each survey divided by the total length in kilometers of the survey route. Relative densities of alligators during 2006 to 2008 were highest in the impoundments and canals of the WCAs (RECOVER, 2009b), of which LNWR supported the highest relative densities (4 to 10 alligators per kilometer), corresponding to 4^{th} quartile restoration targets. Densities in central and southern WCA 3A (1.4 and 2.8 alligators per kilometer) fell in the 2^{nd} quartile. Relative densities of alligators in ENP (less than 1.4 alligators per kilometer) were consistently low, and fell within the lowest quartile for the Everglades, indicating populations were extremely low compared to restoration targets (RECOVER, 2009b).

Relatively low alligator densities in ENP occurred where withholding of water deliveries reduced hydroperiods to less than one year in a ridge and slough landscape that, under natural conditions, is characterized by multi-year hydroperiods (RECOVER, 2009b). The results indicate that shortened hydroperiods and a lowered water table reduce the aquatic habitat and prey base required for alligator survival and reproduction (RECOVER, 2006).

Body Condition

Semi-annual capture surveys are performed along the same routes as described for density surveys in order to determine the body condition of alligator populations. Body condition is a ratio of body length to body volume and is calculated using a Fulton's K condition factor (Zweig, 2003). Differences between the areas surveyed were not evident for body condition.

Fulton's K values for alligator body condition consistently ranged within 2nd and 3rd quartile values of 9.4 and 11.3 (RECOVER, 2009b).

Comparable body condition of alligators throughout the Everglades suggests that contrasting hydrologic regimes may not have as great an effect on alligator body condition as on population density (RECOVER, 2009b). Low body condition throughout the system is consistent with the low biomass of aquatic prey organisms throughout most of the system most of the time (RECOVER, 2009b). The 2009 System Status Report (SSR) speculates that alligator body condition may be inherently low in an oligotrophic wetland such as the Everglades (RECOVER, 2009b). It further states that, under that paradigm, multi-year hydroperiods and natural water level recession patterns provide aquatic habitat that sustains higher population densities of alligators, although low production of food organisms limits alligator body condition (RECOVER, 2009b). Studies by Jacobsen and Kushlan (1989) and Dalrymple (1996) indicate that alligators in the southern Everglades (*i.e.*, Shark River Slough and Shark Valley in ENP) have extremely slow growth rates, which they attributed to food resource limitation.

Mercury Bioaccumulation

Several researchers have studied levels of mercury bioaccumulation in Everglades alligators over the past decade, which appear to be higher in the Everglades than in other states (Yanochko et al., 1997) and other regions of Florida (Jagoe et al., 1998). The reason is not clear, but it is thought to be due to regional differences in sources of mercury, or variation in mercury methylation (Jagoe et al., 1998). Rumbold et al. (2002) measured mercury levels in 28 alligators captured along a transect that included LNWR (*i.e.*, WCA 1), WCA 2, WCA 3, Big Cypress, and ENP. They found that mercury levels were two-fold higher in ENP than in the other compartments; however, mercury levels in alligators seem to have declined since 1994, at least in WCA 3N (Rumbold et al., 2002). Potential explanations for this decline include decreased mercury emissions and the lack of drydowns during the late 1990s, which may have reduced the frequency or amplitude of methylmercury pulses to the system (Rumbold et al., 2002), which have been observed under drought conditions (Krabbenhoft and Fink, 2001). For more information on mercury in the Everglades, see ***Section 3.1.5***.

Summary

In summary, alligator monitoring data over the past decade indicates that the negative trends described by the Restudy remain present. At the time the Restudy was published, data indicated alligators had abandoned the marl prairie and rocky glades landscapes because of shortened hydroperiods (USACE and SFWMD, 1999). At that time, densities of alligators and their holes were greatest in the WCAs and Shark River Slough; however, reproduction was found to be suppressed in Shark River Slough (USACE and SFWMD, 1999). Recent data indicates that alligator densities remain relatively higher in impounded areas with multi-year hydroperiods, including the WCAs, but are lowest in ENP, including Shark River Slough, where hydroperiods have been reduced to less than one year (RECOVER 2009b). Research indicates that mercury bioaccumulation in alligators remains high, particularly in ENP, although levels may be declining. These findings suggest that current hydrological operations are continuing to produce negative biological responses in Everglades alligator populations, and that these populations may be under even greater stress than in 1999, as indicated by lower relative densities in Shark River Slough.

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4.2.1.2 Wading Birds

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Mercury Contamination

Mercury exposure can cause direct negative effects on the health, behavior, survival and reproduction of wading birds as well as indirect effects on prey animal populations. Mercury exposure has decreased markedly (more than 80 percent) in wading birds and their prey between the early 1990s and 2000 (Rumbold et al., 2001; Frederick et al., 2004), but some areas (Everglades National Park [ENP]) still have high exposure. Effects in most vertebrates are dose and species dependent. Although nestling Great Egrets and White Ibises may be largely protected from mercury effects because growing feathers absorb circulating mercury (Spalding et al., 2000a; Herring et al., 2009) fledglings with grown feathers are no longer protected. At levels that may be experienced in the Everglades, Great Egret fledglings on low doses (0.1 parts per million [ppm] wet weigh (ww) in diet) experienced markedly reduced mass, appetite, and changes in behavior, all of which are likely to lead to increased fledgling mortality in the wild (Spalding et al., 2000a&b). Mercury also has been shown to alter circulating levels of estradiol and testosterone both in free ranging ibises in the Everglades (Heath and Frederick, 2005) and in controlled experiments with captive animals (Jayasena, 2010). In controlled experiments, even low levels of chronic exposure typical of the Everglades (0.05 – 0.3 ppm ww in diet) led to endocrine disruption, altered courtship behavior, and widespread male-male pairing in ibises (to 55 percent of pairs). In a lab situation without external stressors typical of the wild, these levels of exposure were associated with an average of 30 percent reduction in reproductive success (Jayasena, 2010). An inverse relationship has been demonstrated between numbers of ibises breeding and feather concentrations over time (Heath and Frederick, 2005), suggesting that mercury has influenced reproduction at the population level in the Everglades, and a three to five times increase in nesting numbers of several species has been associated with a reduction of exposure of 80 – 90 percent. However, it is not clear that all or even most of this increase is due to a decrease in mercury exposure. The 55 percent reduction in breeding pairs demonstrated in captive ibises (Jayasena, 2010) shows that a gross decrease in mercury contamination may have accounted for a substantial part of the population increases. However, it is hard to translate this to the wild birds, since they sub-lethal effects at much lower exposure levels than do captive birds (Spalding et al., 2000a). The effect in the wild could therefore have been of a considerably greater magnitude than demonstrated in captivity. While exposure is currently much reduced by comparison with the 1990s, mercury availability in food webs is in large part controlled by hydrology and sulfate availability, suggesting that mercury exposure could be strongly affected by water management and restoration activities. In summary, mercury exposure remains a potential threat that can have strong influences on wading bird populations.

Ecology

A main theme in wading bird research is the importance of water levels on population and breeding success. Pulses in productivity is highly correlated with droughts (Frederick and Ogden, 2001), possibly from release of nutrients by draw downs, drought-induced predatory fish decline, and surges in crayfish populations (Dorn and Trexler, 2007). Wading bird abundance (presence) is also related to vegetation community and water level, though water level has the greatest effect (Bancroft et al., 2002). Regression models can be used to predict the number of foraging birds for the year in Everglades National Park using three predictors: surface water in the Park in January, dry-down rate, and the amount of disruption in the drying process (Russell et al., 2002). Gawlik experimented with wading bird attraction to sites in two separate studies. One determined the effect of prey density and water depth (Gawlik, 2002), and the other found that water depth, not water depth fluctuation, is most important to wading bird foraging. Social cues (decoys) were equally as attractive as water depth (Gawlik and Crozier, 2007). The relationship of the prey-base to hydroperiod and water depth suggests that over-drained regions do not support the populations of wading birds they could potentially. Wood stork nesting, particularly, is dependent on ENP lands that have been deprived of natural freshwater flows.

The primary driver of wading bird nesting is the availability of food (Frederick and Ogden, 2001; Frederick, 2002; Gawlik, 2002; Herring, 2008). While prey availability is determined by hydrologic variables, vegetation, and prey community structure, avian reproduction focuses simply on seasonal prey production and availability (Frederick, 2000; Herring, 2008). Wading bird nesting event success is correlated to the pulse of prey biomass following drought years, as recently evidenced by the 2008 drought and successful 2009 nesting year (SSR, 2009). However, nesting success does not appear to be dependent on maintaining high biomass of prey at the end of the wet season, if recession rates of water proceed without hydrologic reversal (SSR, 2009). Optimal recession rates during the dry season for wading bird nesting success range between five and seven millimeters per day (Gawlik et al., 2009). It is important to note that some species are more sensitive to hydrologic conditions than others due to foraging behavior. Exploitive species such as the great egret are less sensitive to habitat condition year-to-year than white ibis which are selective searcher foragers (Gawlik, 2002; Beerens, 2008; Gawlik et al., 2009). Hydrologic management decisions based on the evaluation of wading birds should keep this differential response between species in mind.

Population trends (McCrimmon et al., 1997; Crozier and Gawlik, 2003; Brooks and Dean, 2008) and scale (Strong et al., 1997; Allen, 2006) were also popular topics. Wood Storks and White Ibis have declined since the 1930's (Crozier and Gawlik, 2003), but Wood Storks have made a slow recovery throughout the 1980s (McCrimmon et al., 1997). Great and Snowy Egrets have declined as well as Tricolored Herons (McCrimmon et al., 1997). Great Egret nesting has increased, as have their large nesting events (Crozier and Gawlik, 2003). Nesting has moved from the southern Everglades into the central section since the 1980s (Crozier and Gawlik, 2003). Wading birds are considered excellent indicators of restoration, and four metrics were suggested (Frederick et al., 2009): timing of nesting by storks, ratio of nesting ibis + storks to Great Egrets, proportion of all nests located in estuarine/freshwater interface, and interval between years with exceptionally large ibis nestings.

Several papers were simple reports of previously unseen phenomenon or simple topics: intraspecific predation in juvenile White Ibis (Herring et al., 2005) and a non-breeding female tending multiple nests (Herring and Gawlik, 2007). One author reported the successful development of deoxyribonucleic acid (DNA) loci by polymerase chain reaction (PCR) for two Wood Stork populations in Brazil and Florida (Tomasula-Seccomandi et al., 2003). Another reported that adult birds can be surprisingly more vulnerable to fire than nests, which are strategically located in less fire-prone areas than foraging habitat (Epanchin et al., 2002). Power lines were not found to be a significant problem for migrating/foraging wading birds in south Florida (Deng and Frederick, 2001).

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4.2.1.3 Oysters (*Crassostrea virginica*)

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The eastern or American oyster (*Crassostrea virginica*) is a keystone estuarine species. Oyster reefs serve as major structural components of estuaries (Coen et al., 1999; Dame, 1972) by providing habitat for a wide variety of organisms (Bahr and Lanier, 1981; Meyer and Townsend, 2000). As filter-feeders, oysters help improve general water quality and afford secondary benefits such as enhancing light penetration and growth of benthic microalgae and seagrasses (Nelson et al., 2004). The responses of oyster populations to physical parameters (e.g., salinity, temperature, dissolved oxygen) are being examined in south Florida's estuaries to establish current conditions as well as derive relationships between physical parameters, the health of oysters, and the health of the ecosystem. Conditions that promote oyster reef development have been shown to be optimal for other estuarine organisms and may be indicative of restoration success (RECOVER, 2009).

The relationship between salinity and oyster survival, reproduction, and reef maintenance is complex. Due to their sessile nature, oysters are sensitive to sustained salinity extremes, especially during specific life stages and at the wrong time of year. Salinities too high may promote predation and disease (Volety, 2008; Volety et al., 2009), whereas short durations of low salinities may kill predators (Butler, 1985; Owen, 1953). In Florida, the antagonistic effects of high temperatures and low salinities in warmer months and low temperatures and high salinities in cooler months tend to keep disease intensity and prevalence low (Volety, 2008; Volety et al., 2003; Volety et al., 2009). Extended low salinities have been associated with oyster mortality (i.e., 5 [practical salinity units] psu for juveniles and 3 psu for adults) (Volety et al., 2003); thus, sustained excessive freshwater inflows may kill entire populations of oysters (Gunter, 1953; Schlesselman, 1955; MacKenzie, 1977). The observation that oysters can occur in fully marine waters (Wells and Gray, 1960) may indicate that local conditions, such as inter-tidal nature and temperature, may enable oysters to acclimate to local conditions and vary in their responses to salinity. Thus, it is important to evaluate oyster responses within the context of local estuarine environments (Berquist et al., 2006).

Urbanization, expansion and interconnection of drainage basins, and large-scale water management practices in south Florida have increased freshwater discharges during the wet-season and reduced flows during the dry-season. The resulting extremes in estuarine salinity regimes reduced the expanse of live oyster reefs, impacted the timing and extent of oyster reproduction, and affected the diverse flora and fauna community that inhabits oyster reefs. Restoration aims to: (a) re-establish natural freshwater inflows patterns; (b) remove muck; and (c) introduce artificial substrate to promote oyster recruitment (RECOVER, 2009). The Lake Okeechobee Regulation Schedule Study (LORSS) was implemented in 2008 to allow operational flexibility in reacting to wet and dry conditions in the Lake Okeechobee/Kissimmee Basin; this is one effort towards increasing dry season flows and reducing the frequency of high discharges to the estuaries.

Oyster monitoring programs have been established to study five aspects of oyster ecology: (1) density of adult oysters; (2) physiological condition; (3) reproduction and recruitment; (4) juvenile oyster survival and growth and (5) prevalence and frequency of disease (i.e., *Perkinsus marinus* [dermo]) (RECOVER, 2009). Existing reefs in the northern estuaries (NE) are being mapped to establish a baseline and historical distributions are being utilized to identify areas with suitable habitat conditions for oyster reef re-establishment. A Habitat Suitability Index (HSI) is being established for the Caloosahatchee River Estuary and is being calibrated and validated. The intent is to adapt the HSI approach to other south Florida estuaries (Volety et al., 2005; Barnes et al., 2007).

Southern Coastal Systems: Biscayne Bay, Everglades National Park, and Ten Thousand Islands

Historical information and recent monitoring on oyster populations in the southern estuaries is limited, with studies being nearly a decade old or spanning only one year. Although oysters were abundant in northern Biscayne Bay (Smith, 1896), only modest oyster reefs were common near the mouths of coastal streams in pre-development southern Biscayne Bay (Meeder et al., 1999). Current conditions are poor for oyster reef development and survival. Baseline monitoring was initiated 2005-2007, but due to the paucity of live oysters, was put on hold until implementation of restoration activities (Arnold et al., 2008). During monitoring, only one substantial oyster population was documented, and little to no larval recruitment was recorded (RECOVER, 2009). However, live oysters are present (attached to red mangrove prop roots and abandoned traps) and could serve as a source of spat to repopulate old oyster shell deposits still present at the mouths of primary creek beds along Biscayne Bay's western shore (Bellmund personal communication, unpublished data, 2009). Whether restored flows will exit into Biscayne Bay from these relic creek mouths and allow formation of oyster beds where they used to be, or whether flows will exit through new openings where old oyster shell is not present, will only become known as restoration is implemented. The draft adaptive management plan for the Biscayne Bay Coastal Wetlands project calls for the addition of cultch if the habitat is otherwise suitable.

Within western Everglades National Park, adult oysters (monitored from 2006 through 2008) were found to be widely distributed in Chatham River, Lostman's River, and Broad River but limited in Whitewater, Oyster, and Ponce de Leon Bays. A number of suspected reefs sites were explored and only a few contained populations of oysters (Volety et al., 2008). Trends in oyster populations occurred along an upstream-downstream axis, with higher frequencies of reefs and higher condition indices occurring downstream at the mouths of rivers (Volety et al., 2008). It should be cautioned that this study covered one full recruitment season and coincided with the 2007-2008 water year which was one of the driest years on record. Thus, the resulting high salinities and low spat recruitment may not be representative of normal conditions, but instead due to either salinity stress on adult oysters which impacted fecundity, increased predators resulting from higher salinities, or a combination of both.

In the Ten Thousand Islands, observed differences among oyster populations are attributed to the different salinity regimes among individual estuaries as a function of proximity and timing of freshwater inflow (Volety et al., 2008; Savarese 2003). For example, Faka Union Bay receives excessive freshwater volumes from an expanded and channelized watershed during the wet season, resulting in a highly variable salinity regime. Thus, oyster reefs are small in scale, scarce in number, and displaced seaward in distribution. Based on the monitoring data collected in 2000, live density, productivity, condition indices, and spat recruitment were low in Faka Union Bay (RECOVER, 2009). In contrast, Henderson Creek delivers comparatively small amounts of freshwater year-round to Rookery Bay, and as monitoring data collected in 2000 indicated, resulted in high oyster living density, mean productivity, and spat recruitment (RECOVER, 2009).

Northern Estuaries

Throughout the NE, monitored sites along the west coast contain higher adult densities and received similarly high numbers of recruits (RECOVER, 2009). Higher living densities are observed at the end of the wet season due to spawning and recruitment. Results suggest that recruitment rates are affected by substrate availability and freshwater flows during the summer and fall months (RECOVER, 2009). Oysters within the Caloosahatchee River Estuary actively spawn between May and October, a period that coincides with freshwater releases and watershed runoff. Environmental history (e.g., freshwater release regime, salinity, hurricanes) was found to affect both mean annual spat recruitment and physiological condition (RECOVER, 2009). Although downstream locations in the Caloosahatchee River Estuary experience the highest spat recruitment, survival and growth are poor due to predation and disease characteristic of higher salinities (greater than 35 psu). In contrast, juvenile oysters had the highest growth rates in the upper portions of the estuary (typically less than 10 psu). Oysters in the St. Lucie Estuary suffered mortalities in 2005 and 2008 due to low salinities following storm events; however, salinities quickly rebounded, and juvenile oyster densities not only increased but also had improved growth rates.

Summary

Pre-development conditions were more suitable for the establishment and maintenance of living oyster reef. Modest reefs were present in the mouths of most of the creeks along the western shore of Biscayne Bay (Meeder et al., 1999); significantly more extensive oyster reefs existed in Faka Union Bay prior to construction and operation of the Faka Union Canal (Volety and Savarese, 2001); and relic oyster reefs approximately one meter in thickness were documented in Blackwater, Pumpkin, and Fakahatchee Bays (Savarese et al., 2004). Findings of live oysters on prop roots and other elevated structures suggest that once salinity regimes and substrates are sufficiently restored, live oysters are present to re-establish reefs and significant oyster expansion is possible (Volety and Savarese, 2001).

Strong relationships have been established between freshwater flow, salinity, and oyster health, specifically within the Caloosahatchee and Saint Lucie River Estuaries. Restoring salinity regimes that would foster high condition index, sufficient spat recruitment, high juvenile growth rate, and low disease incidence at upstream locations indicate that, with the provision of suitable substrate and limitation of freshwater flows during the spawning season, oysters would survive and reef development would shift upstream (RECOVER, 2009; Volety et al., 2009).

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4.2.1.4 Prey Fish

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Mercury Contamination

Strom and Graves (2001) compared contamination in Indian River and Florida Bay fish to determine if differences exist and to relate levels of contamination to sources of mercury. Differences were significant between study areas, as was proximity to anthropogenic sources of mercury. Fish from western Florida Bay had less mercury than those from Indian River Lagoon, but eastern Florida Bay had more than the other two study areas. Stable isotopes of carbon, nitrogen, and sulfur were measured in fish from eastern Florida Bay to elucidate the shared pathways of methylmercury and nutrient elements through the food web. These data suggest the dominant source of methylmercury is the benthos and not the watershed. However, uncertainty remains to the relative importance of the watershed and how the Comprehensive Everglades Restoration Plan (CERP) may alter this input of methylmercury (Enas and Crumley, 2005).

Ecology

Three papers use modeling to highlight ecological responses of fish to the environment. Gaff et al. (2004) developed a spatially explicit, age-structured model to look at fish density dynamics to compare management scenarios. The model was a poor predictor with the current input, which was mainly hydrology. DeAngelis et al. (2005) modeled fish populations to show that differences in efficiency of resource utilization and dispersal ability, combined with environmental variability (both spatial and temporal), allow the co-existence of many species that share the same resource. Immanuel et al. (2005) presented the ATLSS ALFISH model.

Several studies investigated the effect of salinity gradients on fish community composition. Green et al. (2006) looked at spatial and temporal patterns of fish community structure along a salinity and nutrient gradient. Their hypothesis was that the nutrient rich system would support higher numbers of fish in the mangrove system, but the results were contrary to that hypothesis. Shark River had lower species richness than Taylor River, which included more freshwater taxa. They suggest difference in topography between the sites limits fish movements in Shark River, but not Taylor River suggesting that connectivity plays a relatively important role in Everglades population dynamics. Although autochthonous fish productivity appears low in the Shark River, Rehage and Robblee (2009) showed that, in the dry season, pulses of freshwater fishes entering the upper regions may act as an prey base or subsidy for important recreational fishes such as snook. Lorenz and Serafy (2006) examined fish communities over an eight-year period that included a 3.5-year period of high rainfall that might mimic historic conditions, and also made comparisons between marine, brackish and freshwater demersal fish communities. Their results suggest that freshwater flow reduction has reduced fish populations. Kelble et al. (2010) found dramatic increases in *Anchoa mitchilli* abundance within Florida Bay during years with low salinities suggesting that lowering salinity in CERP would increase the abundance of a key forage fish in Florida Bay. Moreover, the increase in *A. mitchilli* coincided with a decrease in mesozooplankton abundance suggesting the importance of trophic interactions and the possible occurrence of a trophic cascade that could potentially affect phytoplankton blooms in Florida

Bay. Bachman and Rand (2008) looked at performance of fish under differing salinity regimes, using biological performance measures such as growth and survival. Results show adverse effects of abrupt, acute salinity changes on survival and development.

Two papers suggest that shallow-water refugia are important to native prey-base fishes, but droughts that leave only deep refugia are characterized by predatory exotic fish species (Kobza et al., 2004; Main et al., 2007). Ruetz et al (2005) suggest that drying events are very important to the spatio-temporal patterns of fish populations. Densities of bluefin killifish, least killifish, and golden topminnows are lowest after a drydown and recover slowly. Eastern mosquitofish show no response to drydowns. Rehage and Loftus (2007) showed that mangrove creeks in the upper Shark River estuary also function as dry-season habitats. As marshes upstream dry, large numbers of freshwater fishes move into the mangrove zone. However, the distribution in the estuary appears limited by salinity and is short-lived. Heavy predation by both freshwater and estuarine piscine predators lowers prey numbers later in the dry season, perhaps negatively affecting prey availability for wading birds.

McElroy et al (2003) analyzed allozyme and microsatellite loci to test the hypothesis that gene flow for spotted sunfish is limited by the annual dry-down cycles and levee/canals as barriers to sheetflow. They found support for the first hypothesis, but not the second. This suggests that canals may reduce genetic variation in some fishes through increased connectivity through what would otherwise be considered a metapopulation. Fragmentation was also the topic of interest in Chick et al. (2004) who examined whether variation in abundance and community structure of large fishes varies more at a regional or sub-regional scale, due to fragmentation. Consistent with McElroy et al., regional scale hydroperiod and water management related processes seem to be more important in regulating large fish. Rehage and Trexler (2006) looked at the impact of canals on abundance and structure of Everglades fish and macroinvertebrate communities. Density of all taxa increased in immediate proximity of canals, particularly in the dry-season with few composition changes, suggesting a role for canals as dry-season refugia. Throughout sites, animal densities were positively related to phosphorous concentrations (higher in the vicinity of canals). Thus, increases in predation regimes in the vicinity of canals appear overwhelmed by the bottom-up effect of enrichment.

Taylor et al. (2001) documented intra- and inter-species interactions with small fish in a mesocosm experiment. Juvenile fish were placed in tanks with adult fish and predation by adult mosquitofish was the most significant effect. There was also growth limitation in mosquitofish and sailfin mollies from intra- and inter-specific competition. At high densities, juvenile mosquitofish adjusted their diets. This suggests that evaluation tools documenting food-web interaction may need to account for age-specific roles of small fishes.

Trexler and Goss (2009) presented fish and crustaceans as indicator species for restoration. The hypothesis that restoration of natural hydrologic conditions would recover the timing and location of the prey-base of wading birds, especially for successful nesting has been supported by monitoring efforts. They developed dynamic hydrological targets and set restoration targets for prey density. The larger-sized aquatic prey (greater than 0.2 centimeters), which make up the bulk of the wading bird diet, are disproportionately reduced during drought years. Populations of the prey-base (e.g., marsh fish and pink shrimp) are highly correlated with hydroperiod, fully developing after three to four years (Trexler et al., 2005; Trexler and Goss, 2009). Longer hydroperiods would allow fish to attain larger sizes and provide a wider range of prey sizes to wading birds (Chick et al., 2004). Additionally, wet season prey production can be accurately predicted by dry season prey biomass (Gawlik et al., 2009).

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4.2.2 Comprehensive Everglades Restoration Plan Module-specific Ecological Indicators

The following topic summaries are under the heading “4.2 CERP Indicators of Restoration Success,” under the subheading “4.2.2 CERP Module-specific Ecological Indicators”:

- 4.2.2 CERP Module Specific Ecological Indicators
- 4.2.2.1 Lake Okeechobee
- 4.2.2.2 Northern Estuaries
- 4.2.2.3 Greater Everglades
- 4.2.2.4 Southern Coastal Systems

4.2.2.1 Lake Okeechobee

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Regular monitoring and research on Lake Okeechobee has led to the development of a quantitative understanding of the lake's key ecological drivers, especially since the past decade's juxtaposition of extremely wet years (2004, 2005), drought years (2001, 2006-2008), and hurricanes passing over or near the lake, and the change from a higher (WSE) to a lower (LORS 2008) operating schedule (USACE, 1999; 2007; 2008) created a series of conditions that contributed greatly to the understanding of water level influences on the lake environment. In addition, improved lake topography and bathymetry measurements obtained through the use of LIDAR have increased the ability to evaluate the subtle effects of lake stage on a host of ecological processes (Yan *et al*., 2009).

Given Lake Okeechobee's modern condition (i.e., constrained by the Herbert Hoover Dike, equipped with far more inflow capacity than outflow capacity, lacking any significant water storage in the surrounding watershed, and situated at the nexus of competing upstream and downstream water supply, flood control and ecological needs) it is not surprising that lake stage and its associated parameters are major factors in the lake's ecology (FWC, 2003).

Another major influence on Lake Okeechobee ecology is the impact of exotic-invasive plants and animals. The Florida Fish and Wildlife Conservation Commission (FWC) has estimated that there are as many as 119 exotic animal species in Lake Okeechobee and the surrounding watershed (Ferretier, 2005) while the Lake Okeechobee Protection Program Exotic Species Control Plan (2002) identified 14 species of exotic plants and animals of potential concern to the lake ecosystem. Since that report was written additional species of potential concern have been identified including the rapidly spreading Tropical American Watergrass (*Luziola subintegra)*, and the island apple snail (*Pomacea insularum*), which may negatively impact the feeding and reproductive behavior of snail kites (Kunzer and Bodle, 2008). Other exotic species such as the Mayan Cichlid (Matamoros *et al*., 2005) have also been identified. While a great deal of effort and expense has been directed at controlling, and understanding the ecology of two key exotics, *Melaleuca* (Lockhart, 1995) and Torpedo Grass (Smith *et al*., 2004; Rodusky *et al*. in prep.), new plant species continue to be identified and the effects of the lake's exotic fauna have yet to be investigated.

Although Lake Okeechobee is often viewed as a single geographic entity, evidence indicates that it functions as three semi-independent ecological regions (Phlips *et al*., 1993; Havens *et al*., 1999; Work and Havens, 2003; Maki *et al*., 2004; Work *et al*., 2005; East and Sharfstein, 2006). These consist of a central pelagic zone, which is usually highly turbid and consequently does not support submerged or emergent vegetation and where the majority of the effects of the lake's high internal and external nutrient loading problems (such as blue green algal blooms) are seen. In this region phytoplankton primary productivity is frequently light limited and heterotrophic bacteria play an important role in the food web. A shallower, often clearer, near shore region that, given appropriate lake levels, supports a large submerged and emergent plant community and where phytoplankton primary productivity can be either light, or nitrogen limited, and a littoral zone dominated by emergent aquatic vegetation, which, except at high lake stages, is largely hydrologically isolated from the rest of the lake and behaves like a pristine, low nutrient Everglades system.

Relationships between seasonality, lake stage and lake bathymetry drive the ecology of Lake Okeechobee. Several key hydrologic performance measures which identify and characterize these relationships are presented in The Lake Okeechobee Conceptual Ecological Model (Havens, 2000; Havens and Gawlik, 2005) and institutionalized as Restoration Coordination and Verification (RECOVER) performance measures. The lake stage envelope prescribes an annually fluctuating lake stage between a post dry season low of 12 feet National Geodetic Vertical Datum (NGVD) and a post wet season high of no more than 16 feet NGVD with occasional (decadal) excursions below the envelope to support maximum coverage of submerged and emergent vegetation (Havens *et al*., 2000; Steinman *et al*., 2002; Hanlon and Brady, 2002) and their positive effects on water quality and fisheries (, Havens *et al*., 2005; Havens, 2005; SSR, 2009); while during periodic low lake stages encouraging the natural oxidation of accumulated anaerobic muck sediments and providing windows of opportunity for proactive lake management including organic sediment removal, prescribed burning, and exotic vegetation control activities. Lake stage is also important for colonial-nesting and wading birds and other species including the endangered snail kite (*Rostrahamus socialbilis*) and its primary food source, the Florida Apple Snail (Darby *et al*., 1997, 2002) although for these and other species timing and rate of change of lake stage may be equally, or more important.

Based on observations of the effects of drought and hurricanes on the lake, the excessive high and low stage performance measures define sets of conditions that could result in serious ecological damage to Lake Okeechobee. At stages over 17 feet NGVD turbid, high nutrient water invades the clearer, lower nutrient near shore, and littoral zones shade out submerged aquatic vegetation (SAV) (James and Havens, 2005; Havens *et al*., 2001 a). High lake stages coupled with wind and wave action across Lake Okeechobee's long fetch also physically uproot and destroy submerged and emergent vegetation and the habitat they provide (Havens *et al*., 2004; Havens *et al*., 2005). Although short excursions below the stage envelope are not as harmful as those above, and may even be beneficial if they do not occur too frequently, they could allow the spread of exotic and terrestrial vegetation (Lockhart, 1995; Smith *et al*., 2001), result in loss of historical peat lake bottom, and have negative effects on the habitat of the endangered Okeechobee Gourd (*Cucurbita okeechobeensis okeechobeensis*) (USFWS, 1988). Low lake stages (equal to or less than 11 feet NGVD for three months or more) may also negatively affect wading birds, snail kites, apple snails, turtles, alligators and other fauna.

Remaining within the stage envelope to keep Lake Okeechobee within a desirable range of seasonally appropriate elevations is important. However, rate and directionality of ascension and recession rates are also important semi-independent of lake stage; particularly as they relate to the ecology of plants, wading birds, alligators, the endangered snail kite and its primary food source, the Florida apple snail. Current recommendations are for an ascension rate during the transition from the onset of the wet season to the start of the dry season not to exceed one foot in 30 days (Earth Tech, 2008) as this rate allows aquatic vegetation to acclimate to changing stage and also minimizes flooding and consequent death of incubating Florida apple snail eggs.

Similarly, a slow gradual recession with no reversals in lake stage from the beginning of the dry season to the onset of the wet season is critical to concentrate prey for wading bird nesting, to create suitable lake stages for feeding of migratory waterfowl which make extensive use of Lake Okeechobee in the winter, and to protect alligator nests and Florida apple snail eggs from flooding (Lake Okeechobee Adaptive Protocols Draft, 2010).

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4.2.2.2 Northern Estuaries

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Urbanization of Florida's coastal watersheds, coupled with large-scale water management practices, has altered the floral and faunal communities that historically defined the Northern Estuaries. Water quality parameters within the system exhibit spatial variation and strong seasonality, as distinctive wet and dry seasons drive freshwater inflows and nutrient loads (Iricanin and Crean, 2007; Qian et al., 2007). Freshwater flows to the estuaries are typically too high and variable during the wet season and too low or infrequent in the dry season to optimally sustain well-balanced estuarine biotic communities. On the east coast, a network of drainage canals has expanded the watersheds of the St. Lucie Estuary and Southern Indian River Lagoon such that stormwater deliveries to the coasts have increased eightfold (Graves et al., 2004). This has led to salinity extremes; excess nutrient loading; organic enrichment; accumulation of mucky sediments; and increased frequency, duration, and severity of low dissolved oxygen conditions (Chamberlain and Hayward, 1996; Doering, 1996; Graves et al., 2002; Iricanin and Crean, 2007). These modifications to the estuarine environment are clearly reflected in the patterns of oyster beds, benthic community compositions, and submerged aquatic vegetation (SAV) distributions discussed below (RECOVER, 2009).

Oysters

Please refer to section ***4.2.1.3 Oysters*** for a full discussion.

Benthic Invertebrates

Most adult benthic invertebrates exhibit limited mobility, and taxa vary in their ability to tolerate changes in salinity, organic enrichment, dissolved oxygen content, and nutrient regime. Thus, shifts in macrofaunal community structure can be indicative of changes in the estuarine environment (Gray, 1979; Borja et al., 2000; Boyd, 2002). In the St. Lucie Estuary, species richness and individual abundance tend to decrease in wet months and rebound in dry months due to seasonal fluctuations of freshwater inflow and nutrient loading. This effect is most severe in years with intense rainfall and/or climatic disturbance events (e.g., Hurricane Wilma in October 2005, intense rainfall in October 2007, and Tropical Storm Fay in October 2008) (RECOVER, 2009).

While it is well established that salinity is a major factor governing the ability of a species to successfully inhabit and reproduce in an estuary, data suggests that sediment quality may also be an important factor. Sediments with a high percentage of organic carbon may foster reductions in species richness and abundance; as these materials are microbially consumed, dissolved oxygen levels may decrease and toxic metabolic by-products may become available (Gray et al., 2002; Hyland et al., 2005; Gray and Elliot, 2009). Not only do these conditions inhibit filter-feeders and select for deposit-feeders, but hypoxic soft sediments elicit avoidance behavior in many soft bottom species and hinder larval settlement (Marinelli and Woodin, 2002). During the study period, organic content was highest in the St. Lucie Estuary and lowest at the lagoon sites.

An ecological quality score (M-AMBI) was created to account for the level of diversity and abundance of invertebrate taxa, as well as the proportion of disturbance-sensitive taxa (Borja et al., 2008). Average M-AMBI values indicated that all Southern Indian River Lagoon sites are of "good" (slightly polluted) or "high" (unpolluted) ecological status and exhibited high diversity and abundance. However, M-AMBI values for sites within the St. Lucie Estuary ranged from "poor" (heavily polluted) to "moderate" (meanly polluted) to "good" (slightly polluted) depending upon organic content of the sediments (e.g., sites with good ecological status had lower organic content). Community health and sediment quality improved dramatically at the mouth of the St. Lucie Estuary (RECOVER, 2009).

Submerged Aquatic Vegetation

The mechanisms that drive SAV patterns are complex and include freshwater flows, salinity regimes, water clarity, temperature, and other water and sediment quality parameters, all of which interact to influence seagrass success. Restoration goals include increased aerial extent, improved functionality, and re-established natural species-specific temporal and spatial dynamics of SAV communities. Monitoring occurs at both a landscape-scale (through aerial mapping) and patch-scale (through fixed transects and haphazard deployment of 1-m^2 quadrats).

Historically, the upper Caloosahatchee River Estuary was dominated by the freshwater species *Vallisneria americana* and the lower Caloosahatchee River Estuary and San Carlos Bay were dominated by *Thalassia testudinum* (Burns et al., 2007). However, hurricane water releases since 2004 and the confounding effects of salinity extremes and high turbidity (low water clarity) caused shifts in community compositions. In the upper estuary, low light levels and precipitous increases in salinities (beginning in 2006) led to decreased plant cover and density of *V. americana* and increased dominance of *Ruppia maritime* (Burns et al., 2007). In the lower estuary, a period of low salinity and high turbidity decreased *T. testudinum* abundances and as recovery occurred dominance shifted to the rapid colonizer *H. wrightii* (Wilzbach et al, 2000; Burns et al., 2007). High nutrient loads associated with freshwater inflows have also been shown to negatively affect SAV (Hauxwell et al., 2003).

Freshwater discharges into the St. Lucie River ultimately flow into the Southern Indian River Lagoon, linking both systems. In the Southern Indian River Lagoon, *H. wrightii* and *Syringodium filiforme* were historically the dominant canopy species (Morris et al., 2000); whereas in the St. Lucie, the dominant species was *H. johnsonii*. Each seagrass species has a specific salinity threshold (Irlandi, 2006). *H. wrightii* has the greatest tolerance of both salinity range and variability, and can better adapt to fluctuating salinities at the mouth of the estuary. As distance from the mouth of the St. Lucie increases, the percentage of *T. testudinum* and *Halophila decipiens* increase (Irlandi, 2006). The hurricane events and associated freshwater discharges of 2004 and 2005 caused large coverage and density declines and smaller direct impacts due to burial by shifting bottom sediments. The presence of pioneer species, such as *H. wrightii* and *Halodule johnsonii*, indicated seagrass recovery in shallower portions of the Southern Indian River Lagoon (Avineon, Inc., 2008). As restoration is implemented in the St. Lucie Estuary, the north and south forks are expected to support *R. maritima* (as this species is adapted to lower salinity conditions); the middle estuary is likely to support *H. wrightii* and *H. johnsonii*; and the lower estuary (with the highest salinity and clearest water) is likely to continue to support *H. wrightii*, *H. johnsonii*, and eventually *S. filiforme* (Phillips, 1960; Irlandi, 2006).

Overall, the status of SAV is improving as documented by increases in mapped acreage, recruitment into areas left bare following the hurricanes, and transition from pioneer to canopy species (RECOVER, 2009).

Within the Loxahatchee River Estuary, fluctuations in the percent cover and occurrence of seagrass species occurred along the upstream-downstream gradient. While the upstream sites were dominated by *H. johnsonii* (354 acres) and *H. wrightii* (256 acres), the downstream sites contained higher species richness and percent cover. The central embayment contained the highest seagrass percent cover and diversity due to more stable salinities, low light attenuation, and acceptably appropriate nutrient concentrations (Loxahatchee River District, unpublished data). The lowest percent cover and density was observed in the southwest fork, through which flood control releases are shunted through the C-18 Canal network to the sea (RECOVER, 2009).

In Lake Worth Lagoon, seagrass coverage is greater in the northern segment, as the central segment is severely impacted by turbidity and muck and the southern segment has poor water quality. Substantial loss of seagrass has been attributed to extensive dredging and filling activity and sewage disposal outfalls that at one time directly discharged into the lagoon (PBCERM and FDEP, 1998). After the 2004 hurricanes seagrass cover declined in response to increases turbidity from runoff, discharges from Lake Okeechobee, and burial and scour from wave action (Applied Technology and Management, Inc., 2009). Data collected from 2003-2008 indicate a general inverse relationship between canal discharge (i.e., from C-17, C-51, and C-16) and seagrass presence (Applied Technology and Management, Inc., 2009). Preliminary SAV colonization targets have been set based on water depth, since restoration-enhanced water clarity would increase the depth at which adequate light would allow seagrass to establish (RECOVER, 2009).

Summary

Restoration aims to develop more ecologically aware scenarios for flood management, the frequency and duration of water releases, and point and non-point source pollutants in order to restore natural wetlands, stabilize salinity regimes, improve water quality and clarity, remove mucky sediments, and curtail habitat loss (RECOVER, 2009). It is anticipated that such improvements would increase recruitment potential and lead to increased richness and diversity of a multitude of estuarine and coastal species that depend on holistically restored ecosystems for habitat, prey and reproduction.

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4.2.2.3 Greater Everglades

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Considerable research has been conducted on the hypothesized indicators of ecologically relevant, hydrologic restoration of the south Florida ecosystem. The Everglades support a diversity of organisms that are keenly adapted to natural flows and fluctuations of the hydrologic system. Of the ecosystem components identified as probable indicators system-wide (Ogden et al., 2005; Doren et al., 2009; RECOVER, 2009), the following are at least partial components of the freshwater marshes of the greater Everglades, and represent all trophic levels. Note the linkages between the organisms. For a complete discussion of greater Everglades ecological indicators, please refer to the supplemental issue of Ecological Indicators, Volume 9. Also see the Science Coordination Group 2006 report to the South Florida Ecosystem Restoration Task Force, Indicators for Restoration.

A distinction exists between indicator species and "umbrella" species (Caro and O'Doherty, 1999). An umbrella is a species whose conservation confers protection to co-occurring species in the same region. Single-species conservation strategies target umbrella species that are endangered in an attempt to simplify management (Simberloff, 1997); however, there is no evidence that members of one taxonomic group can serve as effective umbrellas for other taxonomic groups in the Everglades due to the diversity of habitats and stressors of the greater Everglades (Curnutt et al., 2000). Indicators, by contrast, are readily sampled components or species whose distribution, abundance, or dynamics serve as reliable surrogates for the health of the system as a whole. They are directly tied to the key environmental stressors that restoration strives to address.

Landscape Patterning

Overall, the landscape pattern continues to degrade throughout most of the former Everglades (Nungessar, 2009). While, not an indicator "species", the landscape pattern of the greater Everglades can certainly be considered an indicator of hydropattern. What makes the landscape pattern a suitable indicator is that it is fairly responsive to both degraded and improved conditions. Wetter conditions in Taylor Slough have resulted in a shift toward more natural vegetation patterns (RECOVER, 2009). Flattening of the landscape, hence loss of ridge and slough landscape patterning is hypothesized to be the result of a disequilibrium between peat accretion and loss (Ogden, 2005). Specifically, the disappearance of ecotones and ridges is attributed to ponding effects due to impoundment (Zweig et al., 2008), and oxidation of accumulated peat is attributed to over-drained areas (Rutchey et al., 2005; Wu et al., 2006). Sawgrass communities and slough communities each exhibit hydrologic tolerances; however, sawgrass seems to be more persistent in high water conditions than sloughs in low water conditions (Conrads and Roehl, 2007).

Transport of organic matter between sloughs and ridges seems to be an important mechanism of ridge and slough development, suggesting that the resumption of relatively high velocity events, through increased water deliveries and removal of barriers to flow, is a key factor governing this indicator (Larson et al., 2007). Landscape pattern is also a function of the nutrient status of the system. Cattail continues to expand in areas where sources continue to leak phosphorus into the greater Everglades (Rutchey et al., 2008). Nutrient enrichment can sometimes be linked to hydrologic conditions. Soil phosphorus levels are negatively correlated with water depth in the conserved areas suggesting over-drained areas are concentrating phosphorus in association with subsidence due to carbon oxidation (Reddy et al., 2005; Scheidt and Kalla, 2007).

Fire Regime

Fire is an easily monitored component of the ecosystem that is partially dependent on hydrology and vegetation. The fact that fire can also dramatically affect hydrology and vegetation, creates a strong feedback making fire an exemplary indicator of ecosystem health (Fire ecology chapter in Knowledge Gained). Fire ecologists have determined optimal return frequencies for large fires (12-14 years) and small fires (3-5 years) (Lockwood et al., 2003; Slocum et al., 2007). Out of synch fire regimes can dramatically alter habitats and create an alternate fire regime state (Slocum et al., 2003; Beckage et al., 2009; Davies et al., 2009), including communities dominated by invasives (Brooks et al., 2004).

Periphyton

Periphyton is a rapidly responsive indicator of water quality change (Gaiser et al., 2004, 2005; Gaiser, 2006). A landscape-scale tool has been developed (Gaiser, 2009) that predicts ecosystem changes based on periphyton. Periphyton is not only an indicator of water quality, but of hydropattern as well. The edibility of the periphyton mat, and hence the availability of the fundamental component of the trophic chain, is a function of the periphyton community composition which is determined by hydrologic factors. Periphyton availability has been shown to be a limiting factor determining consumer (prey-based fishes and macroinvertebrates) densities (Trexler and Gaiser, 2009).

Prey-based Fishes and Macroinvertebrates

The hypothesis that restoration of natural hydrologic conditions would recover the timing and location of the prey-base of wading birds, especially for successful nesting has been supported by monitoring efforts (Trexler and Goss, 2009). Populations of the prey-base (e.g. marsh fish and crustaceans) are highly correlated with hydroperiod, fully developing after three to four years (Trexler et al., 2005; Trexler and Goss, 2009). Longer hydroperiods would allow prey to attain larger sizes and provide a wider range of prey sizes to wading birds (Chick et al., 2004), and perhaps remain in the marsh habitat for longer, instead of moving into deeper habitats (i.e., canals and mangrove creeks), where conditions are unsuitable for wading bird foraging and fish predation is high (Rehage and Trexler, 2006; Rehage and Loftus, 2007).

Inter- and intra-annual variation in the hydropattern is critical to the prey-base, suggesting that fishes and macroinvertebrates are indicators of hydrologic timing. Models are being developed that explore the relationship between wet season prey production and dry season prey biomass (Gawlik et al., 2009). Drought years disproportionately reduce larger-sized aquatic prey (more than 0.2 centimeters), which make up the bulk of the wading bird diet. However pulses of high biomass of the prey-base for wading birds were observed in the wet season following drought years due to heavy recruitment of crayfish (Hendrix and Loftus, 2000). To promote the use of these organisms as restoration indicators, a landscape-scale model has been developed to evaluate hydrologic scenario performance in terms of prey-base targets for restoration (Trexler and Goss. 2009).

Wading Birds

Wading bird nesting is greatly reduced and at different locations compared to the pre-drainage period (Ogden, 2006). The primary driver of wading bird nesting is the availability of food (Frederick and Ogden, 2001; Frederick, 2002; Gawlik, 2002; Herring, 2008). While prey availability is determined by hydrologic variables, vegetation, and prey community structure, avian reproduction focuses simply on seasonal prey production and availability (Herring, 2008). Wading bird nesting event success is correlated to the pulse of prey biomass following drought years. However, nesting success is not dependent on maintaining high biomass of prey, if recession rates of water proceed without hydrologic reversal (RECOVER, 2009). Thus, successful nesting years are indicative of the correct hydrologic timing.

Incorrect hydroperiods and lack of freshwater flow have caused the wood stork nesting to decline in Everglades National Park (ENP) (RECOVER, 2009). All wading bird species do not respond similarly to hydrologic disturbance. White ibis are more sensitive to year-to-year habitat condition than great egrets, becoming more selective of foraging sites and lowering their clutch size (Gawlik et al., 2009). Frederick et al. (2009) suggest that wading birds be used as an indicator of restoration success through the following four metrics: timing of nesting by wood storks, ratio of nesting ibis + storks to great egrets, proportion of all nests located in estuarine/freshwater interface, and interval between years with exceptionally large ibis nesting events.

Alligators

Alligators have long been considered iconic indicators of Everglades ecosystem health. Although alligators are robust and can survive in human-altered environments, the following findings support monitoring alligators as an indicator species: Alligator densities are highest in the Arthur R. Marshall Loxahatchee National Wildlife Refuge, where multi-year hydroperiods persist (Mazzotti et al. 2009). Since restored ridge and slough hydropatterns should maintain long hydroperiods in the sloughs, monitoring of alligators in these areas would help to indicate whether a multiyear hydroperiod has been restored. Body condition also has been shown to be related to water levels, prey production, and prey availability, therefore body condition may be a reliable indicator of restored hydrology and prey conditions (Mazzotti et al 2009, Rice and Mazzotti 2007). However, observation suggests that the unnatural eutrophic conditions of the Everglades may also affect body condition, which suggests that further research may be needed to clarify this topic (Mazzotti pers. comm.). Occupancy rates of alligator holes is an effective indicator in the marl prairie landscape since alligator hole occupancy is related to alligator density (Rice and Mazzotti 2007). Unnatural patterns of alligators and alligator holes in relation to canals (fewer alligators and alligator holes in marshes within one kilometer of canals) are additional reasons the alligator are effective indicators for ecological responses to ecosystem restoration (Rice et al. 2005).

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4.2.2.4 Southern Coastal Systems

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The shallow marine waters of the Southern Coastal Systems (SCS) provide critical nursery habitat for both offshore and resident fishery communities. As the most downstream component of the Everglades ecosystem, the SCS integrates multiple upstream hydrologic changes, such as those proposed by the Comprehensive Everglades Restoration Plan (CERP). Thus, processes that occur within, upstream and offshore of Biscayne and Florida Bays and the southwestern Florida coast are reflected in the abundance and diversity of fish and invertebrate species, several of which serve as biological indicator species for the CERP Monitoring and Assessment Plan (MAP) (RECOVER, 2005; RECOVER, 2009a) and are discussed below. Restoration activities are expected to improve freshwater flows to the estuaries and restore salinity regimes more characteristic of the area. Flows that maximize the overlap of favorable salinity with favorable bottom and/or shoreline habitat support the greatest faunal abundance (Browder and Robblee, 2009).

Fish Communities
Spotted seatrout (*Cynoscion nebulosus*), act as good indicators of estuarine condition as they spend their entire life history within their home embayment and are highly dependent on the surrounding environmental conditions. Within Florida Bay, juvenile spotted seatrout show a significant correlation with salinity. During periods of lower salinity, they expand their geographic range (Thayer et al., 1999) and are observed at higher frequencies in central Florida Bay (Kelble et al., 2009). However, when hypersalinity is prevalent juveniles are largely absent from the north-central sub-region of Florida Bay. Additionally, larval spotted seatrout distributions are independent of salinity (Powell et al., 2003) suggesting a salinity-dependent recruitment cue or increased juvenile mortality during hypersalinity. Data suggests that minimizing hypersalinity would likely increase the population of juvenile spotted seatrout within Florida Bay.

Juvenile abundance indices for piscivorous fish in south Florida mangrove habitats is well correlated with abundances of adult species over the reef tract one to two years later (Jones et al., 2010). This suggests that the mangroves of south Florida provide critical nursery habitat for commercial and recreational fishery species; however, the functionality of mangrove habitat is not geographically homogeneous. Snappers, grunts, and barracuda juveniles utilize specific mangrove habitats within south Florida (Faunce and Serafy, 2008) suggesting a higher importance of protecting these more heavily utilized areas. Moreover, the abundance of juveniles is inversely correlated with salinity (Serafy et al., 2007). However, the salinity preference of gray snapper, *Lutjanus griseus,* is distinct from field observations (Serrano et al., 2007).

Pink Shrimp Communities
Pink shrimp (*Farfantepenaeus duorarum*) density in the estuaries varies regionally and seasonally, possibly due to differences in salinity regimes, benthic vegetation, and accessibility

to settlement-stage larvae (Browder et al., 2005a; Browder et al., 2009; Browder and Robblee, 2009; Criales et al., 2010). Densities are higher in western Florida Bay than Biscayne Bay and the southwestern mangrove estuaries (Robblee and Browder, 2008). Present throughout the year, pink shrimp are most abundant in late summer and fall following the summer peak immigration of postlarval pink shrimp into the SCS, mainly western Florida Bay, from offshore spawning grounds (Browder and Robblee, 2009). Data suggest that year-to-year variation in the supply of postlarvae affects juvenile pink shrimp density; however, it is unknown how the associated fisheries of adult pink shrimp impact the numbers of eggs and larvae available to re-enter Florida Bay. Additionally, patterns suggest that pink shrimp densities reflect annual processes rather than annual fall recruitment, as evidenced by high water deliveries from 1993-2005 resulting in high pink shrimp densities and back-to-back drought years with extremely low flows into Florida Bay (2006 and 2007) resulting in low densities (Robblee and Browder, 2009).

Laboratory trials documented that salinity and temperature significantly affect the growth and survival of small juvenile pink shrimp from western Florida Bay. Survival was high over optimal ranges of salinity (25-35 practical salinity units [psu]) and temperature (20-25°C), but decreased sharply at extremes (Browder et al., 2002). Field monitoring further supported the strong relationship between salinity and pink shrimp. In Biscayne Bay, pink shrimp density was positively correlated with salinity in the dry season with maximum densities occurring at 30-35 psu (Browder et al., 2009). Salinities over 45.3 psu negatively affected mean fall densities of juvenile pink shrimp in Johnson Key Basin ($r^2 = 0.19$, $p = 0.0483$, and $n = 20$) (Browder and Robblee, 2009). This suggests that pink shrimp would have a positive response to a reduction in hypersalinity, which has a detrimental effect on production.

Other independent variables such as seagrass composition, density, cover, and canopy height; water depth; and the presence of fish species contribute significantly to pink shrimp density (Johnson et al., 2002, 2005; Browder et al., 2009, Robblee and Browder. 2009). Out of the 19 species of forage fish and macro-invertebrates tested in Florida Bay, pink shrimp were found to be the most closely related to salinity and seagrass (Johnson et al., 2002a, 2005). Between October 2002 and November 2005, a greater proportion of the variability observed in pink shrimp abundance in southern Biscayne Bay was explained by the abundance of seagrass and associated algae than by salinity (Browder et al. 2005b).

Summary

Monitoring the species above has shown that members of the fish and epibenthic communities with an affinity or reliance on freshwater flow, as it affects salinity, can be utilized to document changes due to water management and restoration activities (Browder et al., 2002, 2009; Johnson et al. 2002a, 2002b, 2005; RECOVER, 2009b). Restoration of more natural freshwater flows is expected to positively impact faunal populations by restoring optimal salinity ranges and enhancing benthic vegetation (Browder and Robblee, 2009). Habitat suitability indices are being developed based upon faunal abundance metrics and observed salinities (Serafy and Johnson, 2008), and a simulation model of juvenile pink shrimp growth and survival as a function of salinity and temperature was developed and could be used to estimate water management impacts on shrimp populations (Browder et al., 2002).

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4.3 Human-Environment Interactions in the Everglades

The following topic summaries are under the heading "4.3 Human-Environment Interactions in the Everglades":

- 4.3.1 Changing Land Use and Land Cover in the Greater Everglades Landscape
- 4.3.2 Ecosystem Services as a Planning Tool for Everglades Restoration
- 4.3.3 Exotic and Invasive Species
- 4.3.4 Fire Ecology in Everglades Restoration

4.3.1 Changing Land Use and Land Cover in the Greater Everglades Landscape

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Land cover changes throughout the Everglades Landscape have permanently altered the hydrologic and ecological regimes. During the last century the natural landscape of Southern Florida was extensively transformed through changes in land use related to agriculture, urbanization processes, and the engineered diversion of surface waterways. The federal government and State of Florida are attempting to undo the environmental damage wrought by one hundred years of land cover change that have reduced the Everglades ecosystem to approximately 50 percent of its original extent (R. Walker, 2001).

Land use dynamics are of key importance to conceptualizing the relationship between natural and human systems (Turner and Meyer, 1994) and therefore understanding its effects is vital to the success of restoration efforts.

Land use and land cover (LULC) change occurs when users (or administrators) of land decide to employ its use and resources towards a different purpose (Briassoulis, 2005). This change can produce both desirable and undesirable impacts. Land cover change can occur as a consequence of natural processes, but most land cover changes occur as a result of anthropogenic forces (Nagendra, Munroe, and Southworth, 2004). In the Everglades, LULC change has taken place through a continuous negotiation of multiple objectives, and socio-economic forces representing different constituencies which often present contradictory opinions about its management and future.

Research and new understanding around the effects of LULC change since the Restudy has seen significant. This new understanding has emerged from two basic research lines. First, the interest of diverse scientists on the effects of LULC changes on diverse natural systems and processes. This also responds to the recent emergence and consolidation of land change science (LCS) which seeks to understand land dynamics and its various consequences through an examination of coupled human-environment systems (Rindfuss, Walsh, Turner, Fox, and Mishra, 2004). Secondly, new understandings have emerged through the recognition and subsequent investigation of the effects of demographic growth and dynamics, with subsequent interest in simulating the role and magnitude of such changes in the resulting pattern of land uses in Florida.

The Magnitude of Land Use and Land Cover Change in the Greater Everglades Landscape
During the last century approximately one-half of the 1.2 million hectares once covered by Everglades wetland were converted for human use of agriculture and development (McCauley, Jenkins, & Quintana-Ascencio, 2010). An estimated 50 pecent of the original ecosystem had been lost since 1900, representing a conversion of 6000 km^2 of Everglades wetlands and pine forest, as well as the loss of three of seven physiographic landscapes in the original system (Davis et al., 1994). This conversion of the Everglades land to human use through extensive drainage and flood control has had tremendous impacts on the natural hydrologic regime; this is a major factor in several current environmental problems, including reduced bird populations,

disappearance of wetlands, and declines in aquifer recharge (Browder et al., 1994). More recently, according to Kambly (2010), the broad everglades ecoregion[23] has experienced a 5.8 percent change during the period 1973-2000. Also, another recent study by Walker et al. (1997) indicates that between 1975 and 1986, approximately 2000 km^2 of natural area were converted to human use in the region, which represented 13 percent of the natural land at the start of the period. This represents an annual rate of conversion of 1.1 percent, 60 percent greater than the global rate of tropical rainforest loss in the 1980s (FAO, 1992). Wetland to agricultural land was the most common conversion, with an estimated 348 km^2 (134 mi^2) converted between 1973 and 2000 (Kambly, 2010).

Land Use and Land Cover Change since the Restudy

Since the last Restudy, Florida has become the nation's thirtieth-fastest-growing state in the United States. For instance, during the past years, the state's population has increased approximately 4,400 people per week (National Oceanic and Atmospheric Administration, 1998). As a consequence of this, substantial demands for urbanizable land have increased. Given that most populous counties either have limited supply of urbanizable land or have implemented growth management controls (i.e., Miami-Dade, Broward)[24], most change has occurred in counties with more relaxed regulations or substantial agriculture land for conversion to urban uses. These counties, given their geographic locations, tend to be critical to the hydro-regime and ecological function of the Everglades, positioning such conversions as significant triggers to landscape and ecological disruption. This dynamic of land use conversion is well reflected in the period between 1992 and 2000, where the most significant LULC change was agriculture to development land uses for a total of 60 km^2 of change, or approximately 20 percent of the total change, followed by wetland to non-mechanically disturbed (57 km^2) and wetland to agriculture at 22 km^2 (***Figure 4-12***) (Kambly, 2010).

Several factors or drivers of change contributed to the contemporary regimes of land cover change in southern Florida that have governed the construction of south Florida’s socionature. The first factor can be attributed to the extensive drainage and flood control measures that began in the early 1950s by the Army Corps of Engineers to ensure the continual increase of agricultural and developed land; condition and infrastructure that remains active until today. Another factor is the improved transportation infrastructure which made this region accessible to middle-class tourists and new residents, allowing for the expansion of urban areas (Kambly, 2010). Also the advent of private and public pensions and health insurance enabled large numbers of retirees to settle in this region (Solecki, 2001), and a significant immigrant population that constantly arrives to southern Florida from Latin-American and the Caribbean. Lastly the established agrarian socio-economic culture demanding constant conversion of land has represented an important driver of change (R. T. Walker et al., 1997).

[23] The Everglades ecoregion refers to the southern tip of the Florida peninsula with an extension of 8000 square miles. It is North America's most extensive flooded grassland. It’s also one of the only rain-fed flooded grasslands growing on a bed of limestone in the world.

[24] Miami stablished an Urban Development Boundary (UDB). Development orders for urban development within the boundary will generally be approved through the year 2015, provided that level-of-service standards for necessary public facilities are met

New impacts of land use change have been investigated over the past decade. For instance, recent research indicates that Florida's anthropogenic land cover change is affecting peninsula sea breezes and warm season sensible weather in unforeseen ways (Marshall, Pielke Sr, Steyaert, and Willard, 2004). Also LULC change create adverse effects on broader weather in south Florida patterns including rainfall (Pielke Sr et al., 1999). New empirical studies also show the adverse effects on increased urban and agriculture runoff derived from land use change and associated water pollution into protected areas (Scott et al., 2002), as well as the effects of the expanding road network on species and habitats (Forman & Alexander, 1998). Moreover, studies on LULC change on the urban-wildland interface are indicating changes on breeding system and pollination of narrowly endemic herbs of the Lower Florida Keys (Liu and Koptur, 2003). Other investigations point out that increasing albedo and vegetation cover can be effective in reducing the surface and air temperatures near the ground as well as affect evapotranspiration and anthropogenic heating (Taha, 1997).

Economic studies of LULC indicate that most agriculture to urban transformation is triggered by potential rent as an incentive, driving speculative land acquisitions in areas to be developed (R Walker and Solecki, 2004), a condition that has degreased only with the last real estate and economic crisis. Regarding agriculture land use dynamics, anecdotal evidence suggests the agricultural and urban economies of south Florida initially possessed a certain degree of functional dependency (R. Walker, 2001). Agriculture is losing a protagonist position in land occupation, primarily with regards to the economy of the region. Although farming is a basic sector (Mulkey and Clouser, 1988; Snyder and Davidson, 1994); delivering products to national and even international markets, the most important crop, sugarcane, had sales approaching $.5 billion in 1990, a very small percentage of the region's gross product (Alvarez et al., 1994). All of these factors indicate a trend for a reduction of agriculture activities and therefore further trends from agriculture to urban land uses. Recent research indicates that efforts in land cover transformation to increase suitable areas for agriculture and urban uses affects hydro-regimes of surrounding areas by changing regional water tables. New evidence shows that given subsidence issues, a significant portion of agriculture lands will soon have to be converted to urban use (Stephens, 1956; Snyder, 2005), therefore increasing significant land conversion to urban in ecologically critical areas within the everglades landscape.

Future Changes in Land Use and Land Cover

Pressures from LULC into the Everglades would most likely increase due to population growth. Between 2005 and 2060 Florida's population is projected to double from approximately 18 to 36 million people transforming Florida into a mostly urbanized landscape (Zwick & Carr, 2006). Furthermore, according to Zwick & Carl (2006)…"if indeed, roughly 7 million acres of additional land is converted to urban use, it means 2.7 million acres of existing agricultural land will be lost along with 2.7 million acres of native habitat. It means that 630,000 acres of land currently under consideration for conservation purchase by Florida Forever and/or one of the five water management districts will be lost. And, it means more than 2 million acres within one mile of existing conservation lands will be converted to an urban use, complicating their management and isolating some conservation holdings in a sea of urbanization"… This is largely attributable to a combination of continued domestic and international immigration. How these new inhabitants develop the land, meaning that at which densities and which patterns will determine much of the changes in land use. So it could be said that the physical manifestation of population growth is land use change and the direct effect is the lost of the most important ecologically rich areas.

Land Use and Land Cover Change and Climate Change

Land-use change is related to climate change as both a causal factor and a major way in which the effects of climate change are expressed (Dale, 1997). With the rapid rates of growth in "exurban" counties, today, urban dynamics related to LULC change alone coastal community's present a growing issue mostly with the abetment of climate change and given the acceptance of the increased vulnerability on these communities. According to Vargas-Moreno et al (2010), regarding climate change, inhabitants on coastal communities would tend to one of two things: as sea-level rise, storms and insurance costs increase, local inhabitants would tend to relocate to northern inland portions of Florida creating a competition for land between urban and conservation land uses. Alternatively, inhabitants would leave the state, possibly reconfiguring a new socio-demographic composition of society that would lead to further changes in land use patterns, an increase of pollutants into the Greater Everglades, and post significant demands for water and ecosystems services.

Research by the Massachuttes Institute of Technology (MIT) Department of Urban Studies and Planning on Climate Change Scenarios in the Everglade Landscape, Vargas-Moreno & Flaxman (2010) indicated that based a number of factors such as population growth, future urbanization density and policies, and sea level rise, future urbanization would consume approximately 20 percent of all priority one areas indicated in the Critical Lands and Waters Identification Project (Hoctor, 2008) by 2060. Sea level rise between 3.6 and 31.9 inches will inundate coast protected areas accounting for potential loss between of 2.5 percent and 75 percent of Everglades National Park. Same scenarios indicate that Florida would lose significant amounts of agricultural land. 447,541 acres or 7.37 percent of agriculture area would be lost to new urban land uses by 2060 according to these scenarios.

There are multiple challenges in dealing with LULC change in the Greater Everglades landscape as well as multiple direct or indirect impacts on its fragile ecosystems. Most research after the Restudy suggests more comprehensive transdisciplinary and spatio-temporal approaches to control and manage land use change processes if the goal is to successfully manage the Everglades ecosystem. Special attention must be paid to the rate and type of land conversations as well as in patterns and processes of urbanization, particularly to the density and ecological impacts of new population

1992–2000	Agriculture	Developed	60	20
	Wetland	Non-mechanically disturbed	57	19
	Wetland	Agriculture	22	7
	Wetland	Water	19	6
	Agriculture	Mechanically disturbed	18	6
	Other classes	Other classes	129	42
			305	100

Source: (Kambly, 2010)

FIGURE 4-12: LEADING LAND COVER CONVERSIONS

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4.3.2 Ecosystem Services as a Planning Tool for Everglades Restoration

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As wetlands and natural habitats in Florida are converted to other land uses, services previously provided by natural areas for free are becoming threatened. Recently, awareness has increased of the economic value of the services provided by natural systems; ecosystems are increasingly seen as assets that provide a stream of services meriting careful evaluation and investment (Naidoo and Ricketts, 2006; Turner and Daily, 2008).

In this summary the term ecosystem services refers to the value that people place on ecosystems, which can be roughly quantified in dollars (Costanza et al., 1997; Chee, 2004; Millennium Ecosystem Assessment, 2005; Farber et al., 2006). In 2005, the Millennium Ecosystem Assessment report defined 24 ecosystem services found worldwide, including food production; genetic resources; water purification and waste treatment; air quality; regulation of natural hazards, climate, water, erosion, disease, and pests; pollination; and cultural services including aesthetic values, recreation and ecotourism.

Internationally there are conservation programs that pay landholders for ecosystem services provided by features on their property (Wallace, 2007; Wunder, 2007). The three that are currently receiving the most money and interest worldwide are watershed services, climate change mitigation, and biodiversity conservation (Millennium Ecosystem Report, 2005). Closer to home, ecosystem service payments are contributing the conservation of the Chesapeake Bay watershed (http://executiveorder.chesapeakebay.net/), there are efforts to promote payments for forest lands in the USA (http://www.fs.fed.us/ecosystemservices/), the Natural Resources Conservation Service is dedicating effort to ecosystem services (http://www.nrcs.usda.gov/), and the U.S. Department of Agriculture (USDA) opened an Office of Ecosystem Services (http://www.usda.gov/wps/portal/usda/usdahome?contentidonly=true&contentid=2008/12/0307.xml).b In the case of the Comprehensive Everglades Restoration Plan (CERP), payments for ecosystem services are not being considered but there may be potential, as a planning tool, to measure project benefits in terms of ecosystem services. The U.S. Army Corps of Engineers (USACE) has been involved in a demonstration project where farmers were paid for maintaining reservoirs rather than crops, so the concept of ecosystem services is not foreign (http://www.mvm.usace.army.mil/grandprairie/). The purpose of this paper is to promote critical thinking on whether calculating ecosystem services may be useful for CERP.

Examples in Florida

Lake Okeechobee Watershed Ranches

Economic pressures lead to conversion of ranches to more intensive agriculture or urban development, often resulting in less water storage and higher phosphorous (P) loads. Ranches often have natural communities that provide wildlife corridors, support water recharge and storage, and support many species including threatened and endangered species (Bohlen, 2008). They also have extensive canals, ditches, berms, and water-control structures, originally designed for drainage and irrigation, that can retain water, rehydrate drained wetlands, and reduce P loads (WWF, 2010). The Florida Ranchlands Environmental Services Project (FRESP) is developing a program to compensate cattle ranchers in Florida's northern Everglades region for providing water storage and/or disposal of excess surface water to help restore Lake Okeechobee and the adjoining estuaries. FRESP is expected to provide an incentive against selling land for more intensive agriculture and urban development. Recent studies by the World Wildlife Fund concluded that paying ranchers for the ecosystem services costs less than or similar to securing the services via large public works projects (WWF, 2010).

River of Grass

The Arthur R. Marshall Foundation Science and Technology Committee used a Total Economic Valuation (TEV) to calculate the ecosystem service value of restoring the River of Grass. Given a 40 year life cycle and the restoration of 95,000 acres of flow path, the benefits were estimated to be over $69 billion and costs estimated at $7.6 billion for a potential area of 95,000 acres (Marshall, 2009). The Marshall Foundation's findings agree with those presented in a review of 1,100 studies, where protected areas consistently provided benefits over costs at ratios from 25:1 to 100:1 (TEEB, 2009).

Considerations During Calculation

Identifying ecosystem services requires inventory of sources of human well-being related to nature, such as aesthetic enjoyment, recreation, human health, physical damage avoidance, and food production (Boyd and Banzhaf, 2007). These can be private preferences (ecotourism, property values), public preferences (species protection), or policy-related (capped carbon emissions) (Milon and Scrogin, 2006; Wunder, 2007). During the inventory it is important to understand who the beneficiaries are, where they reside, how they perceive the ecosystem service, and assumptions made during calculations (Naidoo and Ricketts, 2006).

Inventories include indirect values of natural areas. For example, wetlands provide ecological regulatory functions that protect and support economic activity. Valuing these indirect benefits would influence decisions regarding wetland conversion and diversion of wetland resources to other uses (Milon and Scrogin, 2006; Reddy et al., 2008). TEV of a wetland's ecological functions, services, and resources may exceed the economic gains of converting the area to an alternative use (Barbier, 1994). For a recent and detailed review of calculation considerations for ecosystem services (Wallace, 2007).

Cautionary Notes

- When ecosystem services are quantified, some values, such as the intrinsic value of nature and ethical issues associated with conservation, are nearly impossible to count (Naidoo and Ricketts, 2006).
- Conservation costs, such as management costs, are often not considered because they are difficult to estimate across the landscapes (Naidoo and Ricketts, 2006).
- Opportunity costs (forgone alternatives) should be considered in the calculations but are often left out (Naidoo and Ricketts, 2006).
- Short-term and long-term costs and benefits should be calculated (Freeman, 2003)

Documenting ecosystem services is challenging because sites differ in their physical and ecological characteristics, management history, and connection to the surrounding landscape

(Bohlen et al., 2009). Another challenge is the scarcity of systematic information on which to base valuation of ecosystem services (Guariguata and Balvanera, 2009).

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4.3.3 Exotic Invasive Species

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The Restudy recommended controlling melaleuca and other exotic plants and increasing the effectiveness of biological control technologies for non-native invasive species (NNIS) in the Everglades, at an estimated cost of $16,700,000 (USACE, 2009). Since 1999, melaleuca (*Melaleuca quinquenervia*) has been systematically removed from Water Conservation Areas (WCAs) 2 and 3. Removal of melaleuca and Australian pine (*Casuarina equisetifolia, C. glauca*) on public lands has been successful (Rodgers et al. 2010, USACE 2009); however, old world climbing fern (*Lygodium microphyllum*) has emerged as the priority NNIS target (USACE 2009). In 2009, the U.S. Army Corps of Engineers (USACE) issued an Invasive Species Policy memorandum to establish consistent, nationwide guidance for all Civil Works projects and programs for all USACE operation and maintenance activities, consistent with the National Invasive Species Act and Executive Order 13112. Relevant NNIS issues examined since the YB include: impacts of NNIS on native systems, NNIS invasion potential (Evangelista, 2008; Doren et al. 2009), the role of fire in controlling NNIS (Brooks et al., 2004; Ferriter et al., 2008), the control of NNIS, and implications of NNIS in an emerging system (Doren et al., 2009c). Control of NNIS on private lands (Carter-Finn et al., 2006) and coordination among agencies (Doren et al., 2009) continue to impede progress, while NNIS continue to spread, despite $21 million spent by Florida for control (NRC, 2008). Expansion of NNIS is monitored under several state-wide programs (Rodgers et al., 2010; Doren et al., 2009c) and the need to do more than "get the water right" is part of the Everglades restoration (DOI, 2005). This summary is limited to NNIS because of their importance to restoration, even when the goal is an animal population (Antonio and Myerson, 2002). However, non-native animals may compete with natives for food and habitat, alter predator/prey relationships, reduce habitat value, spread disease, and threaten the integrity of flood protection levees and electrical power delivery (Rodda et al., 1997; after Pimentel et al., 2005; Rodgers et al., 2010; others).

Impacts and Mechanisms of Non-native Invasive Species

Impacts of NNIS introductions and expansion include decreased biodiversity and habitat value and subsequent effects on nutrient, fire, and hydrologic regimes (Davis and Ogden, 1994; Lodge, 2005; Reid et al., 2009). While few introduced species become invasive (Mack, 2000; Mazzotti, 2008), and large scale extinction of natives due to NNIS is rare (Gurevitch and Padilla, 2004), six NNIS have replaced approximately two million acres of native habitat in south Florida (Doren and Ferriter, 2001). The best predictor of invasiveness is latitude (Rejmanek, 1996), but extensive research emphasizes the role of disturbance (Brooks et al., 2004; Davis and Pelsor, 2008), competition (Stohlgren, 1999; Garcia-Serrano, 2005; Vila and Wiener, 2005; Evangelista, 2008), seed source (Denslow and Hughes, 2004; ECISMA, 2008), and facilitation (Antonio and Myerson, 2002) in predicting invasions. Therefore, predictions and management based on any one factor (a single side of the coin approach) would be unsuccessful (Stohlgren, 1999). Davis and Pelsor (2008) describe stochastic, short-lived events (e.g. fire) that can alter competitive hierarchies, increase invasion potential, and obscure the cause of the invasion, and therefore, control of the NNIS. In fact, the fundamental causes of invasion and ecosystem engineering by NNIS are not well understood (D'Antonio et al., 1999; Fridley et al., 2004; Sheley et al., 2006,) and may be unique to each invasion. In addition, *de novo*, or emerging, ecosystems are likely hotspots for NNIS (Hobbs et al., 2004; Doren et al., 2009). Alpert et al. (2000) concluded that it is easier to predict invasiveness based on habitat traits (disturbance, environmental stress, and especially, resource availability) rather than on species traits. Finally, native species and NNIS richness are positively correlated at large scales (evidence of facilitation and other ecological phenomena) and negatively correlated at small scales (evidence that native diversity inhibits NNIS or conversely, that NNIS reduce native diversity) (Fridley et al., 2004), suggesting that both large and small scale control strategies are necessary for a success.

Fire

Altered fire regimes reduce the success of post-invasion restoration and increase the risk of fire to inhabited areas (Brooks et al., 2004). Many NNIS are long-lived or persistent and are perpetuated by feedback mechanisms that rely on disturbance (Whisenant, 1990), thereby affecting the succession trajectory of a site (Hobbs et al., 2007). Little is known about the fire regime necessary to enhance native fire-tolerant species or how to use fire management to suppress NNIS (Ferriter, 2008; Langeland and Stocker, 2009), however, targeted NNIS are frequently replaced by other NNIS and managing only sites that are likely to recover is recommended (Reid et al., 2009). Erickson and White (2007) found that prescribed fire and post-fire seeding can increase NNIS, while leaving canopy cover and minimal bare ground at sites may reduce invasion. Native cattails often replace sawgrass and are not addressed by the South Florida Environmental Report ([SFER], 2008), although Miao and Zoub (2009) found that seed density of cattails, but not sawgrass, is reduced by fire. Stevens and Beckage (2010) demonstrated Brazilian pepper removal with fire intervals less than or equal to four years, while individuals may persist for more than 50 years at fire intervals of more than or equal to eight years, and emphasized the need for historical fire regimes. Overly frequent burning reduces plant diversity under many conditions and may provide opportunities for invasive plants to enter new areas (Langland and Stocker 2009). Current Everglades National Park (ENP) fire management promotes pineland restoration and includes NNIS control (ENP, 2009).

Control of Melaleuca and Other Exotic Plants

The SFER (2010) presents a good overview of NNIS (plant and animal) in south Florida. The four priority NNIS are melaleuca, *Lygodium*, Brazilian pepper, and Australian pine (USACE, 2009). Management plans have been developed for three of these and biological controls have been released for melaleuca and *Lygodium* (Rodgers et al., 2010). During fiscal year (FY) 2009, the South Florida Water Management District (SFWMD) treated nearly 65,000 acres of priority NNIS. The decline in the expansion of melaleuca coincides with abundance of the melaleuca weevil (*Oxyops vitiosa*) and three other biological controls (Rayamajhi et al., 2006). Contrary to historic reports, melaleuca transpiration rates are not extraordinary and it does not dry down wetlands (Allen et al., 1997; Sklar et al., 2002; Mazotti et al., 2008), however, allelopathic substances in roots can alter soil biota and facilitate melaleuca invasion (Porazinska et al., 2007). In contrast, *Lygodium* invasion may be mediated by its release from a soil pathogen (Volin et al., 2009). *Lygodium* is predicted to be the most widespread NNIS in the next ten years (Volin et al., 2004; Doren et al., 2009a) and to invade about 38 percent of the Loxahatchee National Wildlife Refuge (NWR) by 2012 (Wu et al., 2006). The Tree-island Exotic Plant Project has been implemented to address NNIS on the especially vulnerable tree islands. Control of Australian pine, while successful, is complicated by local and state initiatives that allow the plant for various reasons. Brazilian pepper is the most widespread NNIS in the SFWMD (Ferriter and Pernas, 2005) and regional management is limited to mechanical and herbicide controls. Relatively new NNIS include downy rose myrtle (*Rhodomyrtus tomentosa*), shoe-button ardisia (*Ardisia elliptica*), and tropical watergrass (*Luziola subintegra)* (Ferriter et al., 2010). Efforts to monitor and control NNIS include indicators under the Comprehensive Everglades Restoration Plan (CERP), study of potential effects of CERP projects on the spread of exotics, the multi-agency Early Detection and Rapid Response (EDRR) program, Digital Aerial Sketch Mapping, SFWMD Tree Island Exotics Surveys, Restoration Coordination and Verification (RECOVER) Vegetation Classification and Mapping program, Regional Environmental Monitoring and Assessment Plan (REMAP) vegetation survey (USEPA), as well as Everglades and Big Cypress National Park Service, Florida Fish and Wildlife Conservation Commission (FWC), and SFWMD control programs, and others.

Restoration

NNIS control is a high priority for CERP planning (RECOVER, 2009). NNIS can alter fire regime, nutrient cycling, hydrology, and energy budgets of a native ecosystem and diminish the abundance or survival of native species (Mack, 2000). NNIS impede restoration of many natural areas and often drive ecological changes that may be irreversible and thus preclude successful restoration (Doren et al., 2009c). Antonio and Myerson (2002) conclude that NNIS may: 1) trigger, and be the focus of, restoration, 2) be the first to (re)colonize following removal or disturbance and subsequently interfere with restoration, 3) leave a legacy, such as a seed bank, that impedes long-term restoration/management, and 4) restore ecosystem function in the absence of appropriate and available native species. Invasion prevention, early detection, and removal of exotics are critical to NNIS control and management (Hulme, 2006). To date, developing effective strategies for NNIS management in large scale ecosystem restorations remains a challenge (Doren et al., 2002; Sheley et al., 2006) partly because there is insufficient science, except for a few species (e.g. melaleuca in south Florida), to set meaningful non-zero targets for NNIS (Doren et al., 2009c). Since the YB, conceptual ecological models (CEMs) have been developed to evaluate species invasion (Doren et al., 2009c) but are not yet integrated into CERP. The stoplight restoration report card updates the status of exotic plant invasions and the results of control and monitoring programs (Doren et al., 2009c).

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4.3.4 Fire Ecology in Everglades Restoration

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Fire was cited as one of the most important issues of Everglades restoration as early as the 1950s (Egler, 1952; Robertson, 1953; Loveless, 1959). Today the issue of how to incorporate fire into the restoration remains unresolved due to the interactions among fire, ground and surface water levels, peat conditions, vegetation, nutrients, and weather conditions (Light and Dineen, 1994; Slocum et al., 2007). Each of these components is presented in respective companion papers. Historic hydrology and fire regimes under which the Everglades developed over thousands of years are no longer synchronized with the biological components of the system. However, the influence of fire on vegetation, non-native invasive species (NNIS), soils, nutrients, and wildlife habitat, and ultimately its impacts on water flows (Schaffranek et al., 2003), require that fire be addressed as a restoration component. There is consensus in the published scientific literature that re-establishing a natural fire regime, albeit not historic due to post-drainage conditions, is critical to successful restoration (Platt, 1999; Swetnam et al., 1999; Lockwood et al., 2003; Slocum et al., 2003; DeAngelis et al., 2004; Beckage et al., 2005;).

Fire Intervals

Fire intervals in the Everglades are a function of season, water levels, peat depth, fuel load, antecedent fire conditions, vegetation, climate, and other factors (Egler, 1952; Loveless, 1959; Lockwood et al., 2003; Beckage and Platt, 2003; Beckage et al., 2005b; Beckage et al., 2009). Historically, lightning fires burned pine savannas and short-hydroperiod prairies during, or during the transition to, the wet season (Egler, 1952; Doren and Rochefort, 1984; Doren et al., 1993; Platt, 1999). Pre-drainage dry season fires were infrequent, but during extreme drought under post-drainage conditions (e.g. 1955-56), water levels receded three to four feet below land surface and vegetation and upper peat layers burned (Gunderson and Snyder, 1994). Fires intensify in El Niño years (Beckage et al., 2003; Lockwood et al., 2003; Beckage et al., 2005a,) and the Southern Oscillation Index (SOI) of El Niño Southern Oscillation (ENSO) conditions have been used to predict wildfire season severity for three month and one year periods prior to a fire (Beckage et al., 2003). Large-scale fires should not be expected more than every 12-14 years (severe drought), compared with small and medium fires at three to five year intervals. However, natural fire may be complicated by incendiary fires and fire management (Wade et al., 1980; Gunderson and Snyder, 1994; Lockwood et al., 2003; Slocum et al., 2007). Controlled burns have been used in Everglades National Park (ENP) since the 1950s to promote natural vegetation and prevent fuel build-up that leads to more severe wildfires and incendiary fires (Doren et al., 1993; after Schmitz et al., 2002). Current ENP fire management promotes pineland restoration, hazard fuel reduction, invasive species control, and special resource needs (ENP, 2009).

Vegetation and Wildlife Community Succession

Research now supports restoration actions focused on natural fire regimes under which fire-adapted communities developed in south Florida, although historical data are limited (Cissel et al., 1999; Platt, 1999; Beckage et al., 2005a). Everglades vegetation historically recovered rapidly after wet season fires, while severe, too frequent, or dry season fires negatively impacted community structure and species composition (Egler, 1952; Glitzenstein et al., 1995; Platt et al., 2002). Frequent early wet season prescribed fires produce a wider range of post-fire conditions than less frequent, late wet season prescribed fires (Slocum et al., 2003). Fire is part of a system of multiple feedbacks that creates a complex temporal and spatial burn pattern (DeAngelis and White, 1994; Lockwood et al., 2003; DeAngelis et al., 2004; Ogden, 2005). Positive feedbacks between fire frequency and savanna trees appear to prevent the conversion of savannas to forests and facilitate the persistence of the savannas, while long-hydroperiod (wet) prairies may act as firebreaks between plant communities (Slocum et al., 2003; Beckage et al., 2009). In addition, low-severity disturbances may provide the resilience necessary for some plant communities to overcome more severe disturbances (Norman et al., 2008; Davies et al., 2009). The seasonal and regional relationships of fire and vegetation are also important to regional scale models developed to predict the Everglades landscape response to water management scenarios, including the ATLSS model (Wetzel, 2001; Duke-Sylvester and Beckage, 2003; DeAngelis et al., 2004,) and the Everglades Landscape Vegetation Model (ELVM) (Wu et al., 2002; 2000). Consequently, defining a “normal” fire regime that enhances the desired conditions requires that regional and seasonal weather patterns be addressed (Lodge 2005). Disturbance regimes such as fire maintain habitat diversity for species (Moran-Lopez et al., 2006; LaPuma et al., 2007; Davies et al., 2009) and prescribed fire can produce a mosaic of successional stages that supports wildlife in different life stages and provides refuge, while severe fires generally burn larger areas and provide fewer opportunities for refuge (Main and Tanner, 1999; Norman et al., 2008). Everglades restoration efforts frequently focus on three endangered bird species: wood stork, snail kite, and Cape Sable seaside sparrow (CSSS) (Lodge 2005). Of these three, the CSSS is the most threatened by altered fire regimes. Previously documented dependence of the CSSS on fire was based on assumptions that marl prairie habitat shifts to woody habitat without fire (Werner, 1975; Taylor, 1981; after LaPuma et al., 2007). However, LaPuma et al. (2007) concluded that fire does not enhance CSSS habitat and is not necessary for the long-term persistence of the bird. Similarly, Cornutt et al. (1998) reported that frequent fires and/or flooding prevent successful breeding in the CSSS. Natural fluctuations in animal numbers are inherent to ecosystems, however, some species populations, such as the CSSS, are so small that further reductions may be disastrous and long term survival of the CSSS depends on preventing large and frequent fires in occupied habitat (LaPuma et al., 2007). The ENP currently uses prescribed fire but does not practice single-species fire management aimed at the CSSS (ENP, 2009).

Non-native Invasive Plant Species

Water management practices have altered vegetation communities and increased NNIS distributions in the Everglades (Ewel, 1982; Krause, 1984; Gunderson and Snyder, 1994; Light and Dineen, 1994; Richardson et al., 2008,) (NNIS are specifically addressed in a ***Section 4.3.3***). Altered fire regimes reduce the success of post-invasion restoration and increase the risk of fire to inhabited areas (Brooks et al., 2004; Ferriter et al., 2008). More specifically, Stevens and Beckage (2010) demonstrate Brazilian pepper removal with fire intervals. The South Florida Environmental Report (SFER, 2008) indicates that information on how to use fire to enhance native fire-tolerant species is limited, as is information on how fire could be used to suppress NNIS. Native cattails that often replace sawgrass are not addressed by the SFER, but research indicates that fire reduces the seed density of cattails, but not sawgrass (Miao and Zoub, 2009). Nutrient accumulation in the Everglades appears to have shifted control of cattail distribution from phosphorus (P) limitation to hydrology and fire (Newman et al., 1998). NNIS control requires plant fuel management and restoration of pre-invasion fire regimes (Newman et al., 1998; Brooks et al., 2004), however, Reid et al. (2009) report that targeted NNIS are frequently replaced by other NNIS following restoration efforts.

Peat, Soils, and Nutrients

Post-drainage peat and soil subsidence due to fire, compaction, and aerobic decay have reduced land surface elevations, increased hydroperiod in some areas, and increased nutrient releases that affect plant succession (e.g., tree island formation) in the Everglades (Ross et al., 2006; Richardson et al., 2008). Peat depths in the pre-drainage northern Everglades commonly exceeded 14 feet (Lodge, 2005), but have declined an estimated three to nine feet in the Everglades Agricultural Area (EAA) and up to three feet in equally large uncultivated areas south of the EAAs (Ingebritson et al., 1999). An estimated 225 years are required to develop one foot (0.30 meters) of peat depth (McCally, 1999). Tree island elevations increase due to peat accumulation and decrease due to burning and oxidation of peat (Givnish, 2008). Wetzel et al. (2005) conclude that tree islands require the P redistribution mechanisms, including ground water upwelling, dry fallout, guano, and subsurface water flows, as well as P concentration on tree islands by fire, for their persistence. Finally, nitrogen (N) and P sequestration via peat accumulation, combined with minimal geological input, is likely one of the reasons the Everglades marshes and sloughs are P limited (Qualls and Richardson, 2008). In summary, fire management is needed to prevent unintended catastrophic effects on peat elevation, tree islands, and nutrient balances in the Everglades.

Climate Change

Bernhardt and Willard (2009), in a study of the formation of ridge and slough communities in the Everglades, concluded that although altered flow and hydroperiod have affected plant community assemblages, the system remains responsive to large-scale climate phenomena such as the North Atlantic Oscillation (NAO). Beckage et al. (2003) also found that under post-drainage conditions, shifts between ENSO phases and associated periodic large-scale fires strongly influence Everglades vegetation and Beckage et al. (2005b) suggest that the climate-fire relationship can provide a means for inferring past fire regimes. A literature synthesis of the potential ecological consequences of climate change in south Florida and the Everglades was compiled by the South Florida Natural Resources Center (SFNRC, 2009) and describes a shift toward a more positive phase of the NAO and an El Niño-like pattern with higher temperatures in the Pacific Ocean. Modest decreases in rainfall and increases in temperature are expected to extend droughts, increase evaporation, reduce recharge in Everglades wetlands and surface aquifers, and have potentially dramatic effects on fire patterns.

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5 CLIMATE CHANGE EFFECTS ON THE EVERGLADES: KNOWLEDGE GAINED

The National Research Council's (NRC's) First and Second Biennial Reviews on Everglades' restoration (NRC, 2006; NRC 2008) present a detailed understanding of climate change and note its critical influence on the outcome of Comprehensive Everglades Restoration Plan (CERP). Unfortunately, there is little peer-reviewed science available on climate change and the Everglades. The information that is available is either at a regional or global scale or is from agency publications with a policy orientation (i.e., not peer-reviewed science).

The information summarized in the following four sections is a collection of the peer-reviewed scientific literature on four topics: (1) projections of sea level rise, (2) climate change projections for the south Florida Region, (3) potential landscape and habitat changes due to climate change, and (4) potential climate change impacts on the built environment. The information summarized here does not constitute an endorsement of any works cited. It is a collection of the most relevant literature on these subjects published since the Restudy.

For an overview of climate change impacts that includes a broader scope than just peer-reviewed scientific research, see "Climate Change in South Florida" (SCG, 2010).

Reference

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5.1 Projections of Sea Level Rise

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The two main sources of sea level rise information relied upon during the Restudy were a U.S. Environmental Protection Agency (USEPA) sea level rise projection method and a subsequent sensitivity test in the South Florida Water Management Model (SFWMM). In 1995, the USEPA published methodology for estimating probabilities of sea level rise (USEPA, 1995). The South Florida Water Management District (SFWMD) extracted the "most probable" sea level rise estimate for 2050 from this publication (15 centimeters or approximately half a foot) and carried it forward for sensitivity testing in the SFWMM (Trimble et al., 1998). This analysis formed the basis for considering sea level rise issues at the time of of the Restudy.

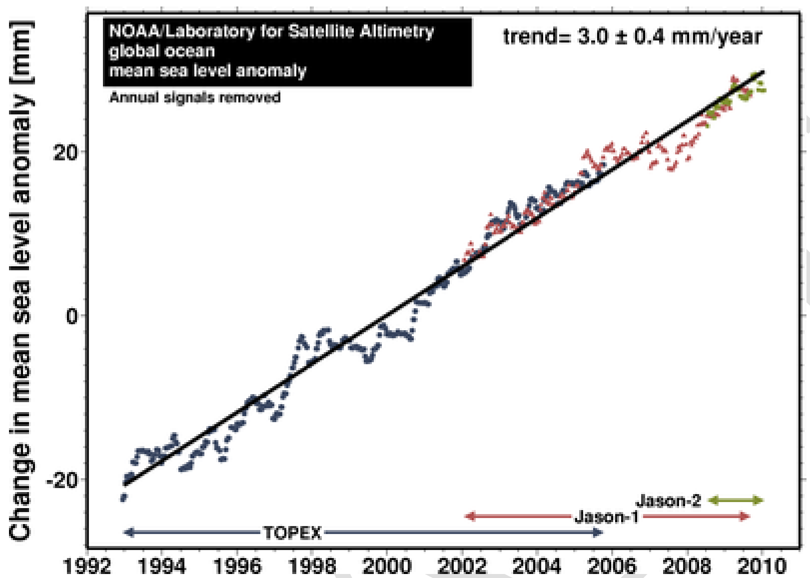
Research on accelerated sea level rise continues to be very active and sea level rise estimates are vigorously debated in the literature. Given the policy ramifications of high uncertainty in sea level rise projections, recent research has attempted to reduce this uncertainty. However, these efforts have not resulted in fundamental change to the sea level rise projections and guidance as stated by the National Research Council (NRC) in 1987 (NRC, 1987).

In 2000, the U.S. Army Corps of Engineers (USACE) incorporated sea level rise information based on previous NRC work (NRC, 1987) into the USACE Planning Guidance Notebook (USACE, 2000). A Comprehensive Everglades Restoration Plan (CERP) guidance memorandum (CGM) on sea level rise, CGM 016.00, was published in 2004 and was based on the same USEPA guidance (EPA, 1995) that was referenced during the Restudy. In the years following the publication of CGM 016.00, various sea level rise projections were presented in the literature, but did not become part of CERP planning. However, in 2009 the USACE issued new guidance on sea level rise in engineering circular (EC) 1165-2-211 (USACE, 2009), which updated the NRC's earlier estimates (NRC, 1987) to reflect new data on global sea level rise rates. The new USACE guidance came with a mandate for application to all USACE projects within the influence of tide. As a consequence of these developments, CGM 016.00 is being updated with this new information and planners are beginning to consider higher sea level rise rates for their projects.

Tracking Actual Sea Level Rise since the Restudy
In 2000, the Intergovernmental Panel on Climate Change (IPCC) published a set of scenarios describing potential future global greenhouse gas emissions pathways (Nakicenovic et al., 2000). Since then, actual emissions have been tracked and have been found to exceed even the highest contemplated emission scenarios (Rahmstorf et al., 2007). Similarly trends in temperature and sea level rise observed since 2000 are above modeled projections based on those emissions scenarios (Rahmstorf et al., 2007).

New Satellite Data Available
Data from coastal tide stations has traditionally been used to calculate global sea level rise trends. However, since 1992 the tide station data has been complemented by global measurements of sea level collected by satellite altimetry (***Figure 5-1***). Satellite altimetry

measures sea level trends with unprecedented accuracy and includes areas inaccessible to land-based tide stations such as mid-oceanic locations. Satellite altimetry has improved understanding of sea level trends, seasonal fluctuations, and spatial distributions of anomalies. Although the first few years of satellite-derived data was available during the Restudy, the record is much longer now and has been analyzed in greater depth.



Source: NOAA, 2010

FIGURE 5-1: **GLOBAL SEA LEVEL RISE DETERMINED FROM SATELLITE ALTIMETRY**

Abrupt Sea Level Rise

Sea level rise projections are often represented in the form of smooth, sweeping lines (i.e., monotonic) that may lead the reader to assume that sea level rise will follow this form. In a report by the US Climate Change Science Program (CCSP, 2008), the authors dispel this misunderstanding and explain that the nature of sea level rise is not always a smooth, monotonic rise, but can be punctuated with pulses associated with rapid ice sheet melting.

Consideration of Higher Sea Level Rise Rates

In the US Climate Change Science Program report on abrupt climate change (CCSP, 2008) the authors examine the possibility of future sea level rise rates significantly higher than modern rates. They noted that during the last two deglaciations, sea level rise averaged 10 to 50 millimeters per year (mm/yr) for periods lasting several centuries (CCSP, 2008). However, extracting sea level rise rates associated with termination of ice ages when much more terrestrial ice mass was present may not be applicable for evaluating rates of rise in the coming century. Researchers have examined the geologic past for more analogous conditions that can provide insight into the range of expected future sea level rise rates. Their efforts have increased the plausibility of rapid sea level rise rates even in interglacial conditions (i.e., warm interval between two glacial periods). Rohling, et al. (2008) noted the last interglacial period was characterized by temperatures at least 2°C warmer than present, resulting in average rates of sea level rise of 1.6 meters per century (16mm per year).

Higher Sea Level Rise Projections for Year 2100

Global sea level rise could significantly exceed one meter by 2100 according to recent research (Overpeck and Weiss, 2009). Pfeffer et al., (2008), as cited in the United Nations Environmental Programme (UNEP) Climate Change Science Compendium 2009 (McMullen and Jabbour, 2009), estimated that a rise of over 0.8 meters is likely, but rise of over two meters is unlikely based on constraints in the plausible rate of ice sheet melting. Vereem and Rahmstorf (2009) developed sea level rise projections based on historic sea level and temperature relationships coupled with projections of future temperature from the IPCC's Fourth Assessment Report. They estimated that sea level rise could rise between 0.75 to 1.9 meters for the period 1990–2100. Even the lowest of these estimates is substantially above the highest sea level rise contemplated during the Restudy.

Progress Toward Restoring the Everglades: The First and Second Biennial Reviews

In the NRC's First Biennial Review (NRC, 2006) a detailed understanding of climate change is presented and its influence on restoration of the Everglades is noted; however, no specific guidance regarding sea level rise is provided. The NRC's Second Biennial Review (NRC, 2008) went on to add specific guidance on how to improve consideration of sea level rise in planning and management.

> *"Changes in sea level will also have significant effects on restoration options and requirements for the Everglades"*. (NRC (2008), Page 49)

The report notes that the probabilistic method used in CGM 016.00 may be inappropriate:

> *"The CERP Guidance Memorandum projected sea-level rise with the probability of 10 percent exceedance at 14 and 32 inches, for 2050 and 2100, respectively and these are very similar to the reasonable upper-end projections. However, to plan based only on the most-probable (mean) sea-level rise of 0.8 feet in 2050, as the Guidance Memorandum suggests, disregards the skewed nature of the probability distribution and the risks of greater acceleration of sea-level rise."* (NRC (2008), Page 52)

The Second Biennial Review also notes that the level of sea level rise considered in CGM 016.00 was too low, that an analysis impacts based on higher sea level rise assumptions should be conducted, and that CGM 016.00 should be amended accordingly.

Engineering Circular 1165-2-211

The USACE issued EC 1165-2-211, *Incorporating Sea-Level Change Considerations in Civil Works Programs* in July, 2009 (USACE, 2009). The EC utilizes an updated version of the NRC's earlier guidance (NRC, 1987) with a change in global sea level rise rate from 1.2 mm/yr to a new, higher rate of 1.7 mm/yr based on recent studies summarized in the IPCC 4th Assessment Report (IPCC, 2007). The CGM 016.00 is being updated to incorporate the guidance of EC-1165-2-211. It will be published as CGM 016.01 in 2010 and will consider higher rates of sea level rise as recommended by the NRC (NRC, 2008). The EC also extends the planning horizon to 100 years, a horizon significantly longer that the 20 and 50 year horizons that were commonly used in the past. The EC uses a scenario approach with projections of high, intermediate, and low (historic) rates of rise rather than the probabilistic approach used by the USEPA (1995).

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5.2 Climate Change Projections for the South Florida Region

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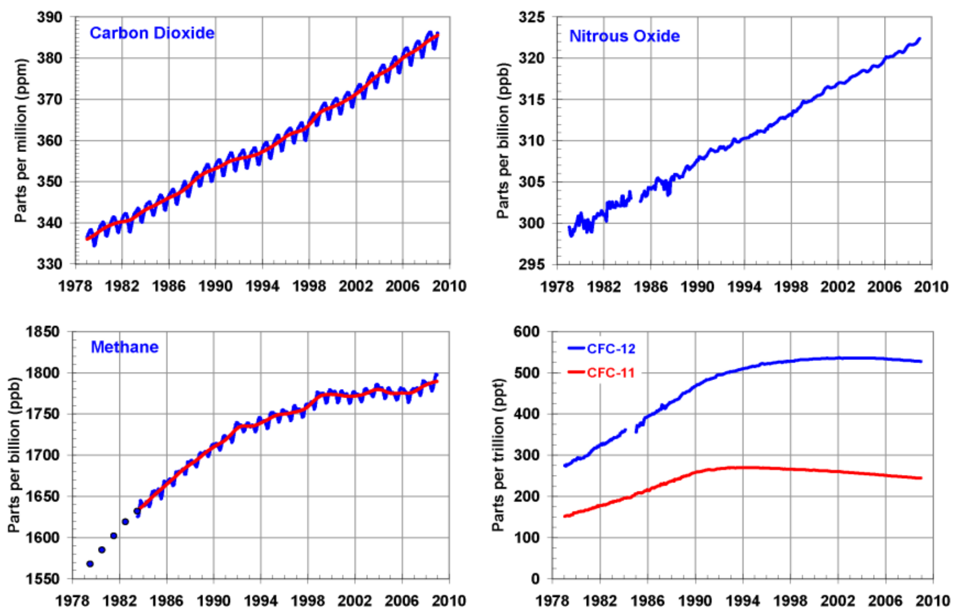
Contributing reviewer: Matt Harwell (USFWS)

The Restudy does not include the words "climate change" and does not contain climate change projections. Climate was not explicitly assumed to be stationary, but non-stationarity was not addressed. Sea level rise was assumed to continue at the historic rate and was considered negligible. Since the Restudy, climate change projections have become more ubiquitous and are now commonly applied in federal water resource projects (Brekke et al., 2009). This paper explains the latest scientific knowledge gained regarding projected global climate change drivers and related effects in the south Florida environment.

Increasing Greenhouse Gas Emissions

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report identifies four principal greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and halocarbons (Forster et al., 2007). These greenhouse gases account for over 95 percent of the radiative forcing by long-lived greenhouse gas increases since the year 1750 (Tans, 2010). Of these, carbon dioxide and nitrous oxide are the only ones that continue to increase at a regular rate (***Figure 5-2***).



Source: NOAA. Tans, 2010

FIGURE 5-2: NOAA ANNUAL GREENHOUSE GAS INVENTORY (TRENDS IN ATMOSPHERIC GREENHOUSE GAS CONCENTRATIONS)

Modeling of Climate Change Effects

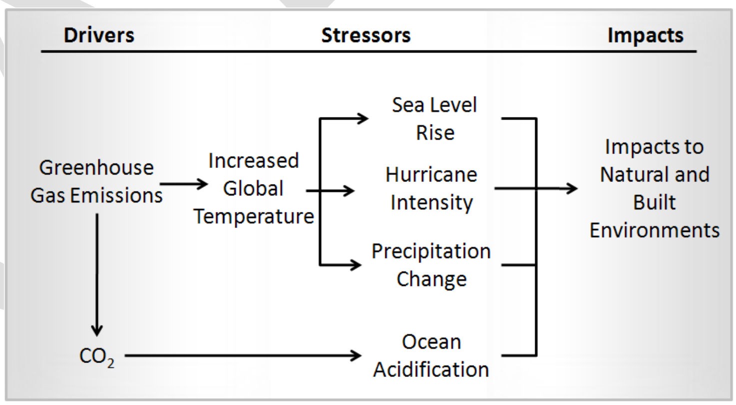
Future climate change is modeled using general circulation models (GCM) that simulate the potential influence of greenhouse gas emissions on global climate. In 2000, just after the completion of the Restudy, the IPCC released a Special Report on Emission Scenarios (SRES) describing a new series of greenhouse gas emissions scenarios to be used as a basis for modeling (Nakicenovic and Swart, 2000). The SRES scenarios described potential future emissions and the global socio-economic conditions that would produce them. The uncertainty in projecting future emissions is a recognized limitation in climate change modeling (Webster et al., 2003). The IPCC SRES scenarios do not include climate policies such as greenhouse gas mitigation (Van Vuuren et al., 2008).

In the decade since publication of the SRES, monitoring of the actual atmospheric concentration of greenhouse gases provides insight into which scenario is being followed. Recent observations show that emissions trended slightly higher than the most extreme scenario, the A1FI (Gangulyet al., 2009). This led Ganguly (2009) to assert that the so called “worst case” can no longer be ruled out as implausible and may even be considered the “business as usual” scenario. A new generation of greenhouse gas emission scenarios has been developed to overcome limitations of the SRES and will be used in upcoming climate modeling in support of the IPCC’s Fifth Assessment Report (Moss et al., 2010).

Climate Change Effects and Impacts to South Florida

The remainder of this paper summarizes the current state of the science regarding projections of climate change drivers and stressors for south Florida including:

1. Increased Temperature
2. Sea Level Rise
3. Changes in Precipitation
4. Ocean Acidification
5. Change in Storms and Hurricanes



Florida does not have a common framework of peer-reviewed climate change scenarios. Climate projections for Florida are available directly from models, or from databases of modeling results, (Meehl et al., 2007). However, results for the State of Florida have not been summarized and published in the scientific literature. In contrast, the State of California developed a set of peer-reviewed climate change scenarios that are referenced as a common platform for planning and management (Cayan et al., 2008). In this paper, studies focusing on the south Florida environment are highlighted where available. However, for many climate parameters results are only available at a larger scale (i.e., regional or global) or remain conceptual in nature.

Increased Temperature

The IPCC reported that Earth’s average temperature is unequivocally warming (IPCC, 2007). The Fourth Assessment Report (IPCC, 2007), presents climate projections at a coarse scale only (e.g., North America). It states that global average surface temperatures may rise from 3°F to

7°F by the year 2099, but would not be evenly distributed geographically. For this reason, one cannot simply add 3°F to 7°F to historic temperatures as an approximation of future climate at a local scale. Temperature projections for Florida at the state or local scale have not been published in the peer-reviewed literature. However, summaries of modeled temperature projections have been produced at a regional scale for the southeastern United States. Climate modeling projections indicate continued warming in all seasons across the Southeast and an increase in the rate of warming through the end of this century (USGCRP, 2009). In the southeastern United States average temperatures are projected to rise by about 4.5°F by the 2080s under a lower emissions scenario. In a higher emissions scenario approximately 9°F of average warming would occur (USGCRP, 2009).

Sea Level Rise

Sea level rise is a critical threat to the natural and built environments of south Florida. Given its level of importance, a separate scientific knowledge gained summary has been prepared on this topic (see ***Section 5.1*****).** It is important to note that current estimates of sea level rise (SFWMD, 2009; USACE, 2009) have not substantially changed from projections made decades earlier (NRC, 1987).

Ocean Acidification

Although the process of ocean acidification has been discussed for decades (Broecker et al., 1979), ocean acidification has recently been recognized as a critical problem in ocean sciences (Kleypas, 2006; Doney et. al., 2009). Ocean acidification is a shift in global ocean chemistry in response to increasing atmospheric carbon dioxide levels. This process lowers the saturation state of carbonate minerals that many marine organisms use to build their shells. The effects of ocean acidification could be pronounced in high-latitude ecosystems in the span of decades (Orr et al., 2005). Recent modeling of ocean acidification in response to a moderate emissions scenario revealed a 2 to 20 percent decrease in global mean marine net primary productivity and export of particulate organic carbon by 2100 relative to preindustrial conditions (Steinacher, 2010). A detailed examination or quantification of the ocean acidification in Florida's coastal waters has not occurred.

Changes in Precipitation

Changes in precipitation due to climate change could include many complex changes in character including seasonal distribution, spatial distribution, intensity, and annual averages. A decline in average annual rainfall is projected for south Florida during this century, due mostly to declines in rain in the spring and summer, (USGCRP, 2009). However, climate models provide divergent precipitation projections (i.e., rain could increase or decrease) for the rest of Florida and the southeastern United States (USGCRP, 2009).

Storms and Hurricanes

The influence of climate change on tropical storm and hurricane intensity has been an area of active research (Trenberth, 2005). However, much uncertainty remains in part due to the difficulty of separating the influence of climate change from natural variability in storm frequency and intensity. Recent studies suggest that the strongest hurricanes may increase in intensity as sea surface temperatures warm (Elsner, 2008; Bender at al., 2010). Hurricanes may become less frequent overall, but those that are formed could have increased intensity (i.e., an almost doubled number of storms of category 4 and 5) by the end of the century (Bender et al., 2010).

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5.3 Potential Landscape and Habitat Changes due to Climate Change

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Climate change and its associated impacts have become a major topic of research in the environmental sciences. In the past ten years, scientific authorities such as the Intergovernmental Panel on Climate Change (IPCC) have recognized an overwhelming consensus that global temperatures are increasing. In addition, it is strongly evident that humans are a major contributor to the warming phenomenon through greenhouse gas emissions into the atmosphere (IPCC, 2007). These warnings have fueled research efforts into regional climate predictions and their associated ecological and social implications. What follows is a summary of recent knowledge gained in the realm of ecological impacts to the Everglades associated with climate change[25].

Generally, south Florida is expected to experience higher temperatures (2 to 5.5 ºC) and lower precipitation rates (10 to 15 percent) during the wet season by the end of the 21st century (IPCC 2007). As a direct result of climate change, less hydrologic input through rainfall and increased evaporation rates can produce more frequent and intense drought-like conditions. This is likely to result in reduced aquifer recharge rates, increased prevalence of fire, and contribute toward exacerbating soil subsidence. Recent sea level modeling, taking into account glacier and ice cap melting, predicts a rise of 0.8 to 2.0 meters by the year 2100 (Pfeffer *et al*., 2008). Finally, Knutson *et al*. (2010) reports a scientific consensus projecting a decrease in the overall frequency of tropical cyclones but an increase in the frequency of the most intense cyclones.

The diversity of ecological communities in the Everglades opposes generalization of ecological effects of climate change. Various species and habitats could have divergent reactions to the anticipated shift in climate (Jifon and Wolfe, 2005). Response to climate change could result in alternative community states as a result of the reaction at the individual species level (Springer and Ward, 2007). For example, Everglades wetland grass and sedge communities may change broadly in response to several variables including temperature, precipitation, drought, flooding, and carbon dioxide (CO_2) levels. Climate warming would allow the expansion of tropical species; however, increased periods of drought and saltwater intrusion may restrict many species.

Twenty-seven rare plant species (Gann *et al*., 2002), four of which are endemic, would be directly affected by sea level rise (Pearlstine *et al*., 2009). Impacts to mangroves would reduce habitat for many species (Odum *et al*., 1992; Meshaka *et al*., 2000). Rapid loss of freshwater wetlands could occur if the natural mangrove and buttonwood berms are overstepped by sea level rise (Wanless *et al*., 1997). Also at risk are the unique woody plant communities of the Everglades including tree islands, coastal hardwood hammocks, and pine rocklands.
Climate change effects on fishes are difficult to predict due to the highly complex interactions between climate, the aquatic environment, aquatic vegetation, species, and aquatic fish communities (Scavia *et al*., 2002), though very real consequences could be realized. Under higher temperatures, cyanobacteria have a competitive advantage over other phytoplankton

[25] This section is a subset of a synthesis on the same subject, written by staff at Everglades National Park (Pearlstine et al., 2009).

species, which could result in highly turbid waters (Paerl and Huisman, 2008). High turbidity stresses submerged aquatic vegetation and benthic invertebrates. Cyanobacteria blooms can deplete the water of oxygen as they decompose, resulting in fish kills. Higher water temperatures could lead to species invasions, as already observed in higher latitudes where climate warming is already having an effect on aquatic systems (Beaugrand *et al*., 2002; Brander 2007). Acidification, due to the dissolution of CO_2 in the ocean, may be a major threat to marine fish species and coral reefs (Feely *et al*., 2004; Graham *et al*., 2006). Increased ocean temperatures may reduce larvae dispersal distances, which fragments populations and reduces genetic drift (Duarte, 2007). Compounding the effects of climate change, overfishing continues to be a major threat to fisheries. The interaction of fishing pressure and climate change on species distributions, size-class, and age structure is likely to be a significant factor to aquatic biodiversity (Berkeley *et al*., 2004; Ottersen *et al*., 2006; Brander, 2007). Finally, if climate change reduces hydroperiods within the freshwater glades, existing shallow pools that act as refugia to small fishes may vanish (Trexler *et al*., 2002). Wading bird populations rely on abundant small fish populations for their prey-base.

Climate change and its impacts to coral through “coral bleaching” have been known for some time (Glynn, 1993; Le Tissier and Brown, 1996). Widespread coral bleaching following high water temperatures has been observed in the U.S. Virgin Islands and the Florida Keys (Patterson *et al*., 2006). Hurricanes may help to cool warm waters, as was observed in the 2005 hurricane season in the Florida Keys (Manzello *et al*., 2007). Coral calcification and growth are significantly limited in water with CO_2 concentrations predicted under conservative climate scenarios (Kleypas and Langdon, 2006). Growth rates, reduced skeletal density, or energetic trade-offs from reproductive processes are all possible coral reef responses to acidification (Hoegh-Guldberg *et al*., 2007; Cooper *et al*., 2008). These stressors can leave the coral vulnerable to competition and invasion of macroalgae (Hoegh-Guldberg *et al*., 2007). Studies have found that healthy herbivorous fish and benthic invertebrate populations can help to counteract declining water quality and macroalgae competition, and should be considered in any coral conservation strategy (Hughes *et al*., 2007; Hoegh-Guldberg *et al*., 2007).

Observed shifts in the timing of breeding cycles in amphibians and reptiles have been attributed to climate change (Parmesan, 2007). Direct mortality of amphibian populations due to climate change could be the result of reduced soil moisture (Corn, 2005) and/or affected immune systems which are temperature dependent (Raffel *et al*., 2006). Amphibians are a particularly sensitive group of fauna that have evolved to thrive in a specific temperature range, and may not be able to adapt quickly enough to the pressures associated with climate change (Fisher, 2007). Crocodiles, which are at the northern end of their geographic range in south Florida should not be directly affected by a warmer climate, though increased salinities and coastal habitat loss may act indirectly on this species (Mazzotti and Cherkiss, 2003). Nesting substrate for sea turtles may become oversaturated due to sea level rise (Foley *et al*., 2006).

Bird breeding and migratory cycles have been an observed effect of climate change (Brown *et al*., 1999; Cotton, 2003; Parmesan, 2007). Migratory clock shifts may not mirror shifts in the availability of prey, which could result in unproductive breeding seasons (Cotton, 2003). In addition, interruptions in the usually seasonal drydown patterns could cause nest abandonment in wading birds (Frederick and Collopy, 1989). The endangered Cape Sable seaside sparrow (reference , under drier conditions and a rise in sea level would likely experience a loss of habitat and prey-base (Baiser *et al*., 2008). The endangered Snail Kite would also experience loss of its primary food source, the Apple snail, due to increased drought frequencies (Martin, 2007; Martin *et al*., 2008). All four avian species of special interest to Everglades restoration, the Snail Kite, Wood Stork, Roseate Spoonbill, and Cape Sable seaside sparrow, require seasonal flooding and drying periods that would need to be maintained in the face of sea level rise (Sustainable Ecosystems Institute, 2007). Other direct climate change effects to these species include increased frequency and severity of fires and storms, loss of freshwater marsh to saltwater intrusion, thermal stress, and changes in phenology (Sustainable Ecosystems Institute, 2007).

Sea level rise and higher storm surges would eliminate or reduce the extent and quality of beach habitat for several endemic mammal species including: Key Deer, Key Largo woodrat, Key Largo cotton mouse, silver rice rat, and Lower Keys marsh rabbit (Backland *et al*., 2008). Manatees may experience reduced survivability under increased storm frequency and intensity (Langtimm and Beck, 2003).

Insects and other ectothermic animals are more vulnerable than other animals to climate change (Deutsch *et al*., 2008; Tewksbury *et al*., 2008). As with birds, shifts in the distribution and phenology of insects have been observed (Parmesan, 2006). Migration and adaptation are possible responses of insect species to increased temperatures, which is the largest insect stressor associated with climate change (Bale *et al*., 2002).

It has become clear in the last decade that Everglades restoration must consider a future that experiences a warmer climate. Restoration targets that rely on a “natural system” that occurred in the past are no longer adequate (NRC, 2008; DOI, 2009). Species of concern will need to be monitored with respect to climate change effects, because responses may vary from thriving populations to complete collapse (Ruhl, 2008). An adaptive approach to management strategies will be necessary in the complex, evolving, and diverse system that is the Everglades. Thus restoration of the resilience of the system through reducing vulnerabilities should be prioritized by creating the semblance of a desired landscape (Pahl-Wostl, 2007).

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5.4 Potential Impacts to the Built Environment

Author: Kris Esterson (USACE Contractor)
Contributing reviewer:

The Everglades, and south Florida's built environment, will both be affected by the impacts of climate change. These two environments are integrated and interdependent. For example, the Everglades share a common watershed with the water utilities serving the communities of southeastern Florida. Similarly, flood mitigation in the built environment depends on water management in the Everglades' watershed. Potential retreat of urban development from the threat of sea level rise could increase density near the Everglades. Given these considerations, successful restoration of the Everglades requires a clear understanding of the stresses and potential responses of the built environment.

Projections of climate change and related impacts on built environment have been understood conceptually for some time (NRC, 1977; NRC, 1987; USEPA, 1989). However, little local detail for the south Florida region was available until recently. Since the Restudy, planning for climate change in south Florida has been active. These efforts have produced a few documents and studies specific to south Florida, but few peer-reviewed scientific publications.

One of the most comprehensive assessments to date is "Southeast Florida's Resilient Water Resources" (Heimlich et al, 2009). This report examines the influence of climate change on water supply, wastewater, water reuse, and stormwater management on southeastern Florida. Sea level rise will affect flood control systems including coastal water control structures, canals, and storm sewers. Many of these early impacts will be felt in southern Miami-Dade County where watertables are already high relative to the area's low elevation above sea level. Flooding in coastal communities will increase in frequency and duration as sea level rises (Heimlich, et al., 2009).

> *"Sea level rise of as little as 3 to 6 inches may begin to compromise the effectiveness of the area's [Southeastern Florida's] coastal flood control structures reducing their capacity by as much as 20 to 40% by 2030. By about 2040, 6 to 9 inches of sea level rise may reduce their capacity by 65 to 70%."*
> – Heimlich, et al (2009)

With stormwater management becoming an increasing challenge, it is possible that urban communities, challenged by the need to dispose of stormwater runoff from intense rainfall events related to climate change, may include discharge to the Everglades as an adaption option (Heimlich et al, 2009).

Water supply in south Florida relies extensively on wellfields placed in the unconfined Surficial Aquifer System (SAS). Saltwater intrusion is already a problem for some coastal wellfields and sea level rise will drive saltwater intrusion further inland (Heimlich et al, 2009). The potential for decreased precipitation could exacerbate this problem as well as reduce overall freshwater available for water supply. In addition water supply for potable uses, lowered precipitation associated with climate change is expected to make supplying cooling needs of electric power plants more challenging (USGCRP, 2009).

Coastal inundation as well as sea level rise could produce elevated damages from storm surges that reach higher elevations and greater distances inland. When coupled with the potential for an increase in frequency of Category 4 and 5 hurricanes (Elsner et al, 2008; Bender et al, 2010), storm surges could provide a significant challenge to the built environment. While sea level rise projections were available at the time of the Restudy, extensive analysis of the impacts of these projections on southeastern Florida's built environment had not been completed. Since the Restudy additional vulnerability assessments have been conducted to detail the potential effects of climate change on major urban areas such as the City of Miami (City of Miami, 2008) and Broward County (Broward, 2010). These assessments often take the form of Climate Action Plans that detail a metropolitan region's vulnerability to climate change and its mitigation options.

> *"Nearly 2000 homes and 200 businesses in eastern Broward would be impacted by a one foot rise in sea level. With a two foot rise, the impact is multiplied 5-6 times with property loss increasing from an estimated loss at one foot sea level rise of $469M to $4.54B. The three foot scenario shows impacts to 11% of the population, 12% of the workforce with 17.5% loss in total taxable value."*
> –Broward County Climate Action Plan (2010)

While most future climate change adaptation options are in the discussion phase, there have been a few adaptation projects that are either under way or completed. The City of Miami Beach has retrofitted storm sewer outfalls with one-way valves to minimize backflow during high tide events. Key West has expanded its network of gravity wells that provide storm water drainage to roadways and augmented some with pumps to assist flow (Luscombe, 2010). The South Florida Water Management District (SFWMD) is planning to upgrade water control structures impacted by sea level rise. The district anticipates augmenting the structures with pumps to move storm water out to sea (Reid, 2010).

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6 ADVANCES AND UPDATES IN PREDICTIVE MODELING

This section of the Scientific Knowledge Gained document does not addresses one of the five components identified by the Committee for Independent Scientific Review of Everglades Restoration Progress (CISRERP) as critical for Everglades restoration (NRC, 2006; NRC, 2008), but provides an important component of scientific knowledge gained since the Restudy.)

6.1 South Florida Water Management Model and Regional Simulation Model

Author: Cary White (USACE)
Contributing reviewers: Walter Wilcox (SFWMD), Luis Cadavid (SFWMD)

There have been many operation and code related improvements to the South Florida Water Management Model (SFWMM) from the Restudy to present. The beginning version for the Restudy was 3.5; the current version being used is 6.0. Release of version 7.0 is pending. Many of the improvements occurred during the development of version 5.5 and those improvements are reflected below and in *Appendix A: Technical Updates* of the *South Florida Water Management Model Version 5.5*. The documentation for version 5.5 (SFWMD, 2005) is the main source of information for this summary. That document and all of the appendices are located in the references at the end of this summary with links to the documents. The operational improvements and improvements related to Everglades Agricultural Area (EAA) inter-basin transfer and stormwater treatment area (STA) implementation have been added as "professional judgment" as no known documentation of these features is known to currently exist.

Operational improvements have been that SFWMM was ported to a Linux operating system (V6.0) and under further development with code enhancements in progress for V7.0. The results of these improvements have been:

- Increased operational flexibility for Comprehensive Everglades Restoration Plan (CERP) Projects
- Increased utility of rainfall driven operations
- Improved Fortran formatting and parameterizationImproved compiler numeric calculationsModified the northern Lake Okeechobee (LO) inflow and modified delta storage (MDS) terms to include basins affected by Northern Everglades planning effortsIncreased model functionality for Northern Everglades features
- Added significant runtime improvements
- Added the ability to run model in continuous (long-term planning) mode or position analysis mode
- Added generic code to provide increased flexibility in modeling scenarios
- Added numerous smaller changes to improve model output and performance

The model simulation period has been extended through the versions.

- The simulation period was 31 years (1965-95) for version 3.5; 36 years (1965-2000), for versions 5.5 and 6.0; and will be 41 years (1965-2005) for version 7.0.

The following highlights data specific changes/improvements from SFWMM version 3.5 to version 6.0 (data updates for V7.0 are pending final approval):

- Re-evaluated and updated 671 new values of topography
- Calculated Upper Kissimmee River inflow via Upper Kissimmee Chain of Lakes Routing (UKISS) Model
- Updated public water supply data

- Calculated Caloosahatchee, St Lucie, and Istokpoga basin demand/runoff and irrigation demands for Lower East Coast (LEC) via Agricultural Field-Scale Irrigation Requirements Simulation (AFSIRS) Model.
- Extended rainfall data input area coverage and created new data set via Tin-10 method
- Changed reference evapotranspiration (ET) calculations interpolation method from inverse-distance squared to Tin-10 method and further refined in the 2005 update to use Pennman-Montieth ET equation
- Implemented land use updates for 2000 and 2050 conditions
- Updated LEC ET-Recharge calculations

There have been miscellaneous operational modifications for structures, gages, and canals through the versions including:

- The ability to simulate canal drawdown during anticipated storms
- Water surface slope along selected canals can vary daily (dynamic canals)
- Operational modifications to several structures to better match structure operational rules
- Small reservoirs can be modeled within and across cells as independent entities

Regional changes around LO and the EAA include:

- Time dependent minimum threshold for delivering water from LO to meet Caloosahatchee and St. Lucie estuarine demands
- Updated MDS based upon new S-236 Basin demand and runoff and S-4 Basin demand time series and updated inflows from Kissimmee River based upon UKISS Model
- Best Management Practice (BMP) make-up water and LO regulatory discharges to the Water Conservation Areas (WCAs) are subject to high water constraints in WCA canals
- Full implementation of water supply and environment (WSE) or Lake Okeechobee Regulation Schedule Study (LORSS) operational schedules for LO (decision trees and climatic features)
- Ability to simulate supply side management (SSM) and other LO water shortage management (LOWSM) as per Water Shortage Rules 40E-21 and 40E-22
- Modified runoff scheme for the 298 Lake Okeechobee Service Area (LOSA) districts
- Ability to do forward pumping (in addition to gravity flow) through structures S-354, S-352 and S-351 when LO is low
- Deviations from LO operational schedule (e.g. drought conditions) can be specified
- Ability to send LO regulatory discharges to LEC tidewater even if WCAs are below schedule
- Days of week can be specified for LO water supply deliveries to EAA and LEC
- Inclusion of Istokpoga Basin demands and runoff time series
- Extended spatial simulation of demands and runoff to include all LOSA basins (e.g. North Lake Shore)
- Inter-basin transfer of water in EAA basins

- Full implementation of Everglades Construction Project (ECP) (also known as full STA implementation)

Changes in the WCAs include calendar-based floor elevations. The model has the ability to send aquifer storage and recovery (ASR) water directly to grid cells. LEC trigger module resolution was refined from six to 21 water restriction zones.

Changes at Tamiami Trail and south through Everglades National Park include the following:

- S12 A, B, C, and D structures are simulated separately
- Tamiami Trail can be simulated with grid cell culvert flow or as a variable length weir to mimic bridge
- Combined Structural and Operation Plan (CSOP) operations are used at and south of Tamiami Trail
- Tidal Creek flows from ENP to Whitewater Bay and Florida Bay are explicitly simulated
- Marsh operations are used in the ENP Buffer region

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Memorandum - South Florida Water Management Model (SFWMM) V5.5x Trigger Module Modifications. memo-trigger_package_v5.5_112006_final.pdf

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- Appendix A: Technical Updates - 102605_icu_rpt_final_app_a.pdf
- Appendix C: Use of NSM as targets for System-wide Performance Measures - 102605_icu_rpt_final_app_c.pdf
- Appendix D: SFWMM Planning Assumptions - 102605_icu_rpt_final_app_d.pdf
- Appendix E: Comparison of Future With and Without Rain-Driven Operations - 102605_icu_rpt_final_app_e.pdf
- Appendix G: Improvements Incorporated into the SFWMM V5.5. - app g upgrades 12-06.pdf

- Appendix L: C Program for Tin-10 Application (Rainfall) - app l tin.cc 8-3.pdf
- Appendix M: Development of Topography Data - app m_november2001elev.pdf
- Appendix N: Upper Kissimmee River Basin Model Technical Memorandum - app n ukiss memo 12-14-1.pdf
- Appendix O: Public Water Supply Memorandum - app o_sfwmm2000_pws1996-2000.pdf
- Appendix P: Preparation of Rainfall Data - app p rainfall 8-3.pdf
- Appendix Q: Brief AFSIRS Description - app q afsirs.pdf
- Appendix R: Development of Reference ET Data Set - app r sfwmm2000_ref_et_selected_method.pdf
- Appendix S: Determination of FLI, FGI, and FLR Parameters - app s fli memo 813.pdf
- Appendix T: Development of Land Use Data - app t sfwmm_v50_landuse_mod.pdf
- Appendix U: Development of LEC ET Recharge - app u et-recharge_lec_2000base_memo.pdf

6.2 Natural System Model

Author: Cary White (USACE)
Contributing reviewers: Walter Wilcox (SFWMD), Luis Cadavid (SFWMD)

The Natural System Model (NSM) is a computer model developed in 1989 using algorithms from the South Florida Water Management Model (SFWMM). The input data, parameters, and algorithms used to simulate the movement of water in the NSM are supplied by the calibrated and verified SFWMM. The NSM attempts to simulate the hydrologic response of the pre-drainage Everglades to the recent climatic inputs by using vegetation-based parameters to compute evapotranspiration and overland flow. NSM version 4.5 (NSM 4.5) was used during the Restudy (1965-1995). NSM version 4.6.2 (NSM 4.6.2) was subsequently developed and has been used for most evaluations (1965-2000). Both NSM 4.6.2 and NSM version 4.6.2 Sens4 (NSM Sens4) were used for the Interim Comprehensive Everglades Restoration Plan (CERP) Update (ICU) evaluations and subsequent projects. The major updates from NSM 4.5 to NSM 4.6.2 and NSM Sen4 are listed below.

- The simulation period was extended from 31 years (1965-1995) to 36 years (1965-2000).
- The period of simulation will be extended to 41 years (1965-2005) to use an updated version of the NSM in conjunction with the update to SFWMM version 7.0.
- The 41-year period of record may be used for Natural System Regional Simulation Model (NSRSM) [Regional Simulation Model (RSM) version of NSM].
- The NSM 4.6.2 and NSM Sens4 data sets and physical parameters are consistent with the SFWMM version 5.4 calibration efforts and the previous NSM version 4.5 is consistent with SFWMM version 3.5 calibration efforts.
- Topography updates were performed for both NSM 4.6.2 and NSM Sens4.
- Subsidence was included in areas north of Tamiami Trail in NSM 4.6.2.
- Improved contoured topography estimates were performed for the entire South Florida System in NSM Sens4.
- The “edge matching” along western boundary of the model domain was refined in NSM Sens4.
- NSM Sens4 contains more consistent predictions across the ridge and slough landscape and better agreement with scientific and historical evidence.
- The NSM Sens4 marl marsh predictions are closer to “best professional judgment” and provide a better hydrological match to historical soil type information.

The discussion related to the future use of NSM-like models in planning efforts is continually evolving. At the August 2008 Greater Everglade Ecosystem Restoration conference, NSM sensitivity was presented by Robert Fennema, Department of the Interior, Everglades National Park (ENP) through a version NSM ENP Mod1. This version of the NSM utilized different topographic and other parameter assumptions than NSM 4.6.2 or NSM Sens4. While Restoration Coordination and Verification (RECOVER) targets currently use NSM 4.6.2, where applicable, information provided by both NSM ENP Mod1 and the NSRSM may be considered in the development of the companion natural system model for the SFWMM 7.0 updates. At this time, there are significant differences in the average annual volume of water crossing a transect running from S140 to S319 [“River of Grass” (ROG) Transect] in the various versions of NSM (Walter Wilcox, SFWMD personal communication).

- NSM 4.6.2 predicts approximately 1.3 million acre-feet/year (NSM Sens4 is estimated to be about the same)
- NSM ENP Mod1 predicts approximately1.9 million acre-feet/year
- NRSRM predicts approximately 2.0-2.1 million acre-feet/year
- As a point of reference, the Existing Condition Baseline (ECB) for the 2008 timeframe predicts approximately 1.4 Million acre-feet/year across the same transect

Efforts to understand these differences and how to use the versions of the NSM models in RECOVER target development are currently ongoing. At present, it appears that the NSRSM may be the most likely candidate for use in conjunction with SFWMM version 7.0.

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6.3 Tides and Inflows in the Mangroves of the Everglades (TIME) Model

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Contributing reviewer: Eric Swain (USGS)

In 1997 at the time of the Restudy, the South Florida Water Management Model (SFWMM) v3.5 was the primary tool used to evaluate the interaction of water supply and demand with hydrologic conditions in Palm Beach, Broward and Miami-Dade counties and portions of seven other counties in south Florida. At that time, it produced a period of record of 31 years starting in 1965. The evolution of the SFWMM to its current version 5.5 is discussed in another of these knowledge gained papers.

After the Restudy, the Florida Bay Program Management Committee (PMC) sent a letter to the U.S. Army Corps of Engineers (USACE) (Armentano and Hunt, 1998) describing the critical gaps remaining in the understanding of the marine ecosystems in south Florida and their links to hydrologic conditions in the southern Everglades. In particular, the PMC focused on the limitations of the hydrologic model as a tool to evaluate the impacts of project alternatives on Florida Bay and other areas of the southern coastal system. They were informed by the SFWMM developers that there was a general lack of confidence in the simulated water levels and flows close to the edge of the model domain (see RECOVER 2006). There was great uncertainty in any of the simulated hydrology close to the coastal boundary.

The difference between the alternatives on Florida Bay was evaluated using a simple regression between the water level gage P33 in Shark River Slough and the salinity station in Whipray Basin. The PMC expressed that this ignored an understanding of relationship between the hydrology of Shark River Slough, Taylor Slough, and Florida Bay. Since the restudy, multivariate linear regression (MLR) equations have been developed and are being used to relate salinity in at Marine Monitoring Network (MMN) stations in Florida Bay and other nearshore areas with water levels at gage stations in the southern Everglades, wind patterns, and sea level variation (Marshall et al., 2003; 2004; Marshall, 2008). The use of the MLR equations has reduced some uncertainty; however, the uncertainty in the simulated water levels provided by the SFWMM at the southern limits of the model remains.

The PMC also made recommendations towards improvement of tools used to evaluate alternatives expressing that models should be able to predict volume and location of flows across the mangrove zone. They recommended coordination with the development of the Surface-Water Integrated Flow and Transport in Two Dimensions (SWIFT2D) model being developed at the time by the U.S. Geological Survey (USGS).

Since the PMC review, the USGS has continued work on a numerical model to achieve a sufficient understanding of coastal freshwater flows for use in evaluating management alternatives related to the Comprehensive Everglades Restoration Plan (CERP). The Flow and Transport in a Linked Overland/Aquifer Density Dependent System (FTLOADDS) code was developed to represent connected surface- and ground-water systems with variable-density flow (Wang et al., 2007). FTLOADDS combines the SWIFT2D surface water code with the SEAWAT ground-water flow and transport code. SWIFT2D is a two-dimensional hydrodynamic flow and transport code with modifications to account for precipitation and evapotranspiration (Schaffranek, 2004). The SEAWAT program is a coupled version of MODFLOW and MT3DMS designed to simulate three dimensional, variable-density, saturated ground-water flow and solute-transport (Guo and Langevin, 2002). The surface water hydrology is coupled with ground water to accurately represent leakage between the embayment and wetland surface water and ground water, which transfers substantial volumes of water and salt (Wang et al., 2007).

The FTLOADDS code has been used in several domain applications within the Everglades to southern coastal system (e.g., south Biscayne Bay, Florida Bay, southwest Florida coast) (***Figure 6-1***). The first application was the Southern Inland and Coastal Systems (SICS) which basically represented Taylor Slough and the C-111 Basin. The need to include Everglades National Park and the southwestern Florida coastal area and better represent the effect of the water delivery control structures lead to the development of the Tides and Inflows in the Mangroves of the Everglades (TIME) domain. The BISCAYNE domain was developed to investigate the CERP effects on surface and groundwater on Biscayne National Park. The two have been combined into the Biscayne and Southern Everglades Coastal Transport (BISECT) domain to cover the entire southern part of the Everglades system in a grid of 500-meter square cells (Lohmann et al., 2008). The overall concept of linking these model domains to the SFWMM is provided in ***Figure 6-2***. Essentially, the BISECT domain using the FTLOADDS code is designed to use the boundary data generated by the SFWMM. It should be noted, as seen in ***Figure 6-1***, that the USGS team has also developed a domain for the Ten-Thousand Islands area using FTLOADDS (Swain and Decker, 2009).

Boundary conditions are defined for both surface and ground-water parts of the model. The surface-water model contains two types of boundaries: areal (wind, rainfall, and evapotranspiration) and lateral boundaries (discharge, water level, no flow, and salinity). Wind is included in the model as a term applied to the momentum equation for each cell computation; scalar wind speeds and vector directions from available weather stations. Volumes of rainfall and evapotranspiration are applied to each cell for each timestep from data collected at stations throughout the domain area. Evapotranspiration data are calculated by using a modified Priestley-Taylor equation that is dependent on water depth and solar radiation. Water depth is simulated at each timestep and solar radiation data is collected at stations within the domain. Lateral boundaries are defined as open (having free exchange of water and salt across the boundary) or closed (having no flow across the boundary). Open boundaries can be described by time series of discharge or water levels (Wolfert et al., 2004). Water levels and discharge values are assigned from the appropriate cells in the SFWMM.

The ground-water model contains two types of boundaries: general-head and no flow (Wolfert et al., 2004). The general head boundaries are at the interface of the SFWMM and the no flow are at the estuarine interface where no data are available.

Periods of field-measure stage, flow, and salinity data have been used to calibrate and verify the various domain applications. The TIME application has been used for time periods within the period of record of the CERP scenario simulations using SFWMM boundary conditions.

The need for a model that produces less uncertain results in the southern Everglades has not changed since it was noted by the PMC in 1998 after the Restudy. In the MLR equations, better tools to use model data in grids that represent the location of current stage gages have been produced. The BISECT (and Ten-Thousands Islands) domain with the FTLOADDS code offers the potential for a better tool in areas where the SFWMM produces less reliable data. Data values from the SFWMM can be transferred to the BISECT application at locations within the center of the SFWMM and used to water levels, flows, and salinities in the south Everglades and coastal areas.

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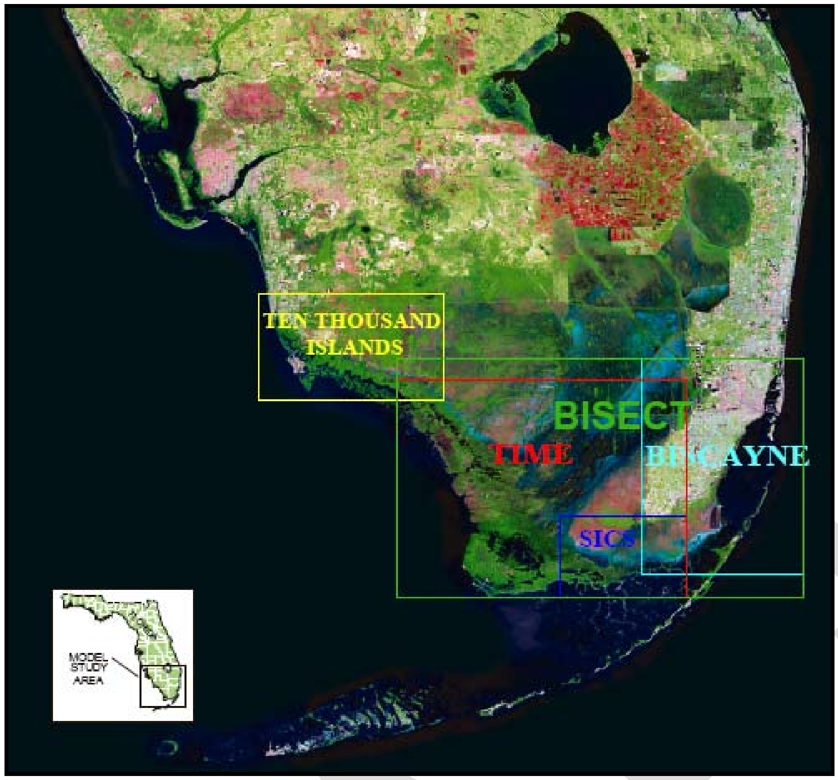
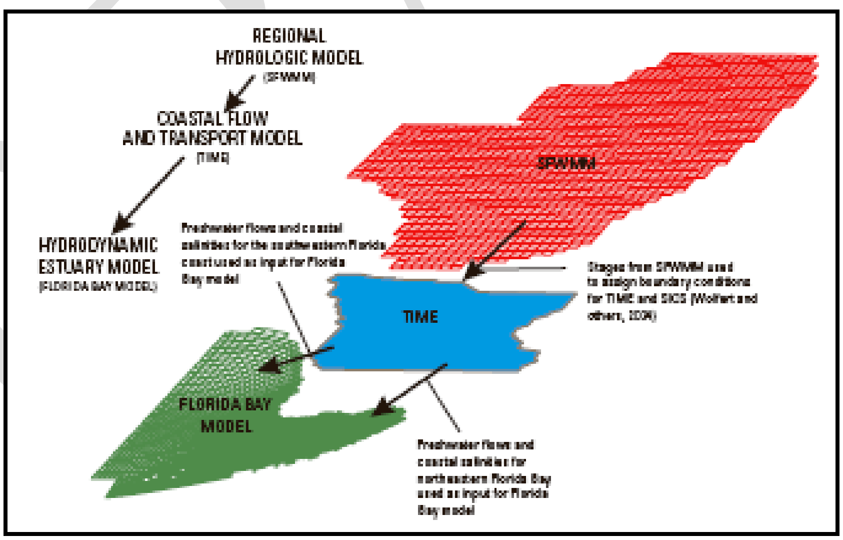


Source : Wang et al., 2007

FIGURE 6-1: LOCATION OF APPLICATION DOMAINS FOR THE FTLOADDS MODEL



Source: Wang et al., 2007

FIGURE 6-2: CONCEPT FOR LINKAGE BETWEEN THE SFWMM, TIME, AND A FLORIDA BAY MODEL

6.4 Modeling to Understand Freshwater Flows Requirements to Achieve Restoration in Florida Bay

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Several efforts are underway to simulate, (i.e. model, hydrologic and salinity) conditions in Florida Bay. Marshall et al. (2009) describes efforts to understand hydrologic and salinity conditions in Florida Bay prior to anthropogenic changes. The method couples paleoecological data on long-term historic ecosystem conditions with statistical models derived from observed meteorological and hydrological data. The hard bodied organism assemblage in sediment cores is used to estimate salinity conditions in the period before water management in south Florida. Multivariate linear regression models have been generated to explain the relationship between salinity at monitoring locations (Marine Monitoring Network Stations maintained by Everglades National Park) in Florida Bay and hydrological conditions (stage at measurement gages) and meteorological conditions (wind and sea level). Marshall et al. (2009) used linear regression to estimate a paleo-based water level (stage) at significant locations in the marsh (P33 and Craighead Pond [CP]) and flow in Shark River Slough (SRS) at Tamiami Trail and in Taylor Slough at Taylor Slough Bridge (TSB). ***Table 6-1*** provides the mean daily values of observed and predicted paleo-based stage and flow, as well as the ratio of observed to paleo-based values for the period of approximately 1990 through 2003. Using the ratio of paleo-based to observed flow at TSB (***Table 6-1***) and the mean 25-year flow of 50,000 acre-feet (62 X 10^6 m^3) at TSB (***Figure 6-3***), results in the average annual estimated pre-drainage flow through TSB of approximately 246,000 acre-feet (2.46 X 10^8 m^3) or about 2.5 times the highest flows through TSB observed in the recent past.

TABLE 6-1: MEAN DAILY VALUES OF OBSERVED AND PREDICTED PALEO-BASED STAGE AND FLOW AT LOCATIONS, AND THE RATIO OF PALEO-BASED FLOW AND STAGE TO OBSERVED FLOW AND STAGE

Location	Observed Mean Value	Paleo-based Mean Value	Paleo-based: Observed
P33 (stage)	1.93	2.48	1.28
CP (stage)	0.39	0.99	2.54
SRS (flow)	42.40	115.8	2.73
TSB (flow)	2.23	8.9	3.99

Source: Marshall et al., 2009
Note: Flow values in cm3/sec; stage values (m) are relative to the NGVD29 datum

Another modeling approach was taken by Hebert et al. (in manuscript) using available models to estimate the freshwater flow required to reestablish a gradient of seagrass communities in the transition zone and into Northeast Florida Bay. They applied the FATHOM hydrological mass balance model to predict changes in salinity regimes in the sub-basins of Florida Bay in response to increasing freshwater inflow scenarios into the transition zone of Florida Bay. A discriminant function model that associates eight seagrass community types with water quality variables including salinity was used to predict the seagrass community type associated with the modeled salinity predicted with increasing freshwater flow. The desired gradient of seagrass expressed in the literature (SFWMD, 2006; Herbert et al., in manuscript) was one of submerged aquatic vegetation species such as *Chara* dominant in ponds in the transition zone with *Ruppia maritima* transitioning to *Halodule wrightii* in the transition zone to nearshore environment. This pattern potentially could also bring stability to the seagrass communities in the central and western basins with the potential for a mixed *Thalassia/Halodule* community in those areas adding resilience of the community to fluctuations in salinity. Herbert et al. (in manuscript) found that the desired goal could be attained with a three-fold increase in freshwater flow from the Everglades to Florida Bay. This is in the range of estimated flow by Marshall et al. (2009) to achieve paleo-based salinity estimates.

Summary

Current attempts to model the amount of flow needed to achieve salinity and seagrass community targets in Florida Bay indicate that two to three times the current average flow is required to meet these targets.

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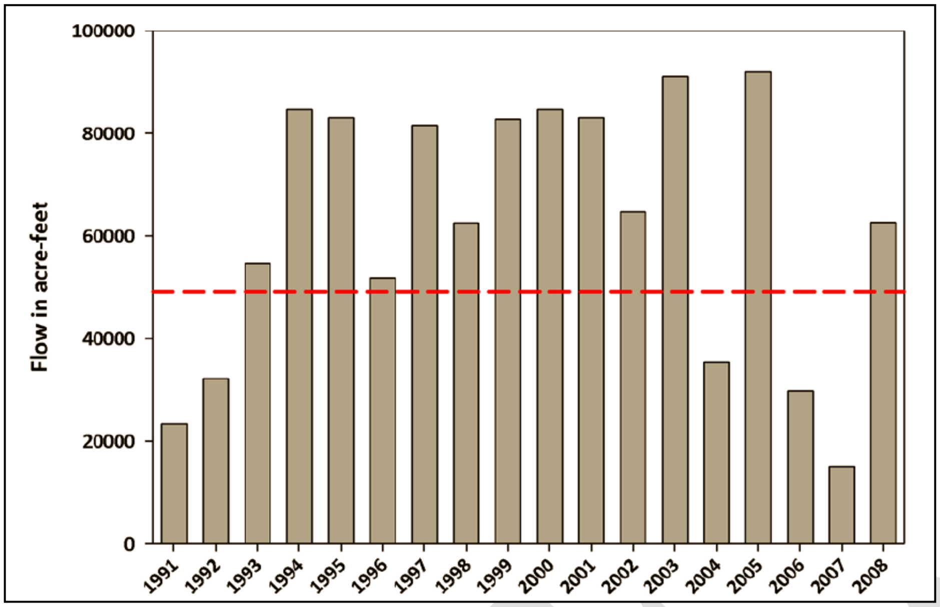

Source: Woods and Zucker, 2009
Note: The red line is the mean 25-year annual flow value.

FIGURE 6-3: ANNUAL FLOW AT TAYLOR SLOUGH BRIDGE IN EVERGLADES NATIONAL PARK