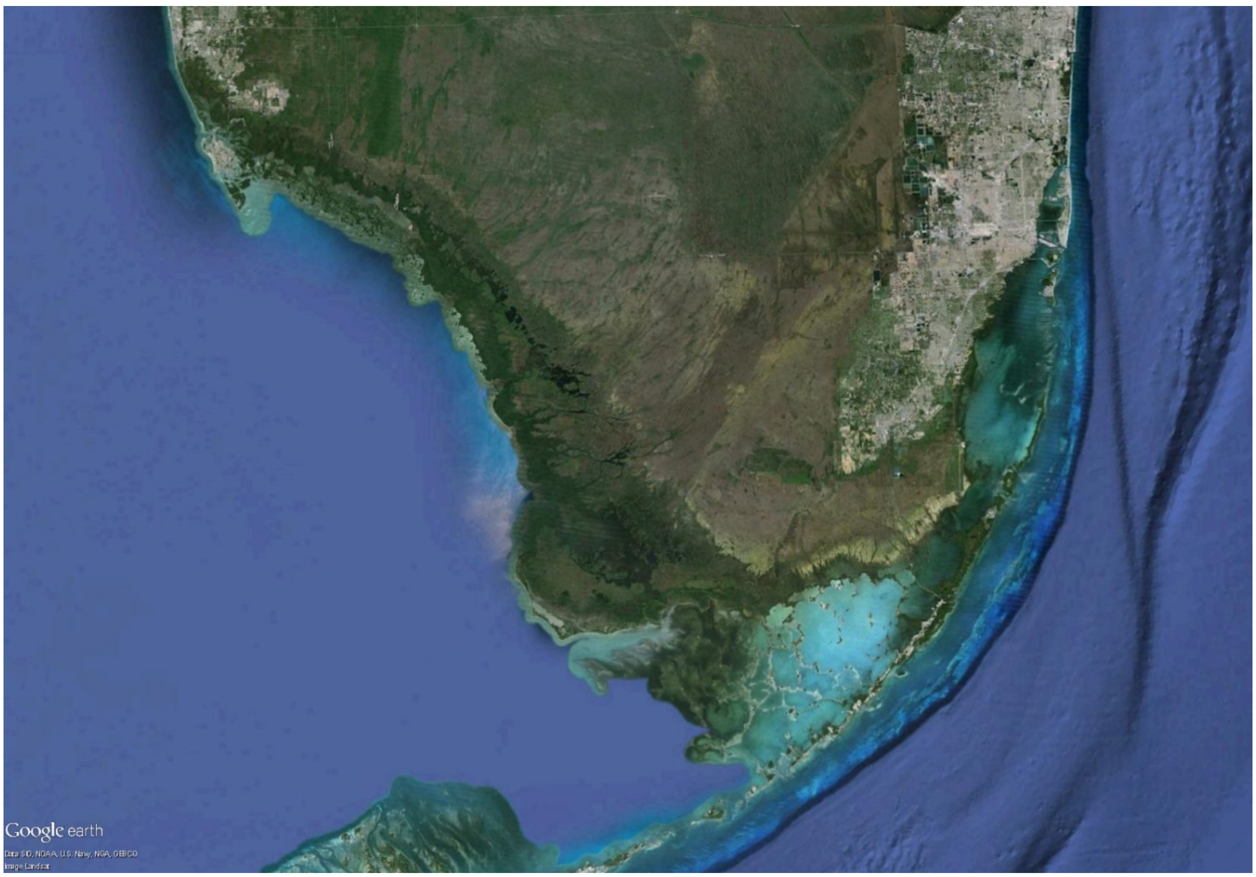
Evaluation of the Effect of Sea Level Rise on the C-111 Spreader Canal Western Project, South Florida



US Army Corps
of Engineers ®
Jacksonville District

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Executive Summary

The C-111 Spreader Canal Western Project is a U.S. Army Corps of Engineers (USACE) project under the Congressionally-authorized Comprehensive Everglades Restoration Plan (CERP). Past USACE construction of local canals for flood damage reduction and water supply benefits had the unintended impact of reducing freshwater flows and lowering water levels in wetland conservation areas along and inside the eastern boundary of Everglades National Park. The project uses pumps to restore historic freshwater flows in targeted wetland areas and provides a linear surface water feature to create a hydraulic ridge that prevents surface and near-surface groundwater from seeping out of the Everglades National Park. The C-111 project is a critical piece in a long-term effort to restore and sustain freshwater flows through the unique south Florida sawgrass wetlands, and to sustain estuarine conditions in Florida Bay and the coastal mangrove forests.

Ecosystem restoration benefits are anticipated from the increased freshwater flows which will benefit significant areas of low elevation coastal wetlands along with the adjacent tidal and near shore shallow marine ecosystems in Florida Bay. Almost all of the project area is less than 6 feet above sea level, with much of the area below 3 feet above sea level in a coastal landscape with low relief, so long term sea level rise is anticipated to affect both the project structures and the project benefits. The USACE Institute for Water Resources Responses to Climate Change Program funded this adaptation pilot study to document the methodology used by the project delivery team to assess the potential impact of sea level rise at 20, 50 and 100 years post-construction. Following USACE guidance, sea level rise was modeled using three curves representing the historic rate of local SLR (per NOAA records from the nearby Key West tide station), an intermediate rate as represented by the National Research Council's Curve I, and a high rate as represented by the National Research Council's Curve III. While this study was conducted independently of the C-111 Spreader Canal Western Project planning and cost-benefit analyses, it was noted that the geographic location of all potential management measures considered was the same such that sea level rise would not have been a deciding factor in decision-making in this case.

At 20 years post-construction, sea level rise is unlikely to exert significant impact on project features or benefits. Under the highest rise (7.4 inches), there is projected to be a 10% reduction in freshwater benefit but only minor effects to nearshore salinity conditions. No significant impacts are noted at lower inundation levels.

At 50 years post-construction, both the intermediate (9.1 inches) and the high (24.5 inches) increase in sea level are projected to affect the project. At intermediate levels, there is projected to be an approximately 10% reduction in freshwater benefit and minor effects to nearshore salinity conditions. At high levels of sea levels rise, there is projected to be a 33% reduction in freshwater wetland benefits and significant shifts in the location of the estuarine zone. Impacts under the lowest level of sea level rise are not significant.

At 100 years post-construction, all levels of sea level rise affect the project. The effects of the lowest rise (8.8 inches) are comparable to the effects of the intermediate rise at 50 years; the effects of the intermediate rise (22.8 inches) are comparable to that of the highest rise at 50 years. At 100 years, the high sea level curve reaches 68.8 inches (>5 feet), completely inundating

the project area and eliminating project benefits; significant location shifts and degradation of nearshore salinity conditions are also anticipated. However, until that point is reach sometime between 50 and 100 years post-construction, significant ecosystem benefits will accrue, providing an essential bridge between current ecosystems and habitats and their future location and configuration.

Finally, the project noted that the water management features established under CERP and prior projects are resilient features: at lower levels of sea level rise, at least some of the impacts could be offset by reoperation of features even as some features become submerged.

This study demonstrated that the sea level rise guidance is straightforward to apply, and produces information that is helpful to decision makers wanting to understand potential future sea level rise impacts. Additional evaluation tools are needed to better understand the diverse hydrologic, geomorphological, and ecological impacts of sea level rise to coastal ecosystems, with a particular emphasis at informing long-term adaptation and sustainability strategies in response to climate change.

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1 - Introduction

For the next 100 years and beyond, sea level rise is anticipated to pose widespread and continuing threats to both the natural and built environments, and to the regional economy of the Southeastern U.S. (NCA report). Because of its low relief and low elevation, South Florida, including the Cities of Miami, Miami Beach, and Homestead, is at particular risk even from modest increases in sea level and/or storm surges.

Much of south-central and southwestern Florida consists of freshwater sawgrass wetlands and, along the coast, brackish-water mangrove ecosystems. Much of the region is protected as Everglades National Park (ENP), Big Cypress National Preserve, and smaller state parks; managed as wetlands (such as Water Conservation Areas (WCA) 1-3); or farmed to provide food for people (Everglades Agricultural Area (EAA)). Historically, the natural ecosystems were sustained by surface and near-surface flows originating in Lake Okeechobee, flowing south through the EAA and WCAs into ENP, where much of the water then flowed southwest through Shark River and Taylor Sloughs to Florida Bay (Figure 1). Diversion of a large share of this flow has resulted in significant degradation of the greater Everglades ecosystem.

WRDA 2000 authorized the Comprehensive Everglades Restoration Plan (CERP), and the plan includes restoration of sufficient surface water to sustain these unique south Florida ecosystems. The C-111 Spreader Canal Western Project is a U.S. Army Corps of Engineers (USACE) subproject under the CERP umbrella. The goal of this project is to restore wetland conservation areas near and inside the eastern boundary of Everglades National Park which have been impacted by past construction and operation of the adjacent C-111 Canal.

The C-111 Canal is located southwest of the City of Homestead at an elevation less than 6 feet above current sea level, which means that sea level rise could impact the project during its 50-year lifetime. Consequently, the USACE Institute for Water Resources Responses to Climate Change Program funded a study by the Jacksonville District (SAJ) to document how the project delivery team investigated the potential future impact of sea level rise on the C-111 Spreader Canal Western Project features and the restored flows to ENP these features will provide.

1.1 Background

Population growth, agricultural development, and industrial and municipal water demands in South Florida have radically transformed regional surface and groundwater flows. As a consequence, the extensive wetlands that comprise the Everglades ecosystem have been reduced in area and quality, with much of the land drained and put to agricultural uses. Canals and ditches installed over the past century by public and private interests to aid land development efforts have often negatively impacted natural hydrologic conditions currently divert a substantial percentage of flows away from the remaining wetlands, including those preserved in ENP.

These primary water management canals and related features in this area ditches were the result of U.S. Army Corps of Engineers' *Comprehensive Report on Central and Southern Florida for Flood Control and Other Purposes* (1948) and subsequent studies. The Comprehensive Report proposed a long term comprehensive plan to develop flood control, water supply and other benefits needed for human settlement and land development in about 50% of South Florida. Most of the remaining areas of South Florida were retained in a largely undeveloped condition that now includes Everglades National Park, the very extensive Water Conservation Areas located north of ENP up to the agricultural areas south and east of Lake Okeechobee, and the Big Cypress National Preserve. On the basis of this report, Congress authorized and funded detailed design and construction of the Central and Southern Florida Project (C&SF) for Flood Control and Other Purposes. The project employed levees, water storage, channel improvements, and occasional use of massive pumps to create a complex regional water management system. The project also installed a 100-mile East Coast protective levee to separate Everglades flood waters from sprawling urban development along the Lower East Coast of Florida. This plan attempted to reduce flooding outside the park and rehydrate-water areas within the park using a combination of drainage reduction and wetland restoration-watering, and resulted in Congress establishing the Central and Southern Florida Project (C&SF) for Flood Control and Other Purposes. The project employed levees, water storage, channel improvements, and large-scale use of massive pumps to supplement gravity drainage. The project also installed a 100-mile perimeter levee to separate the Everglades from sprawling urban development.

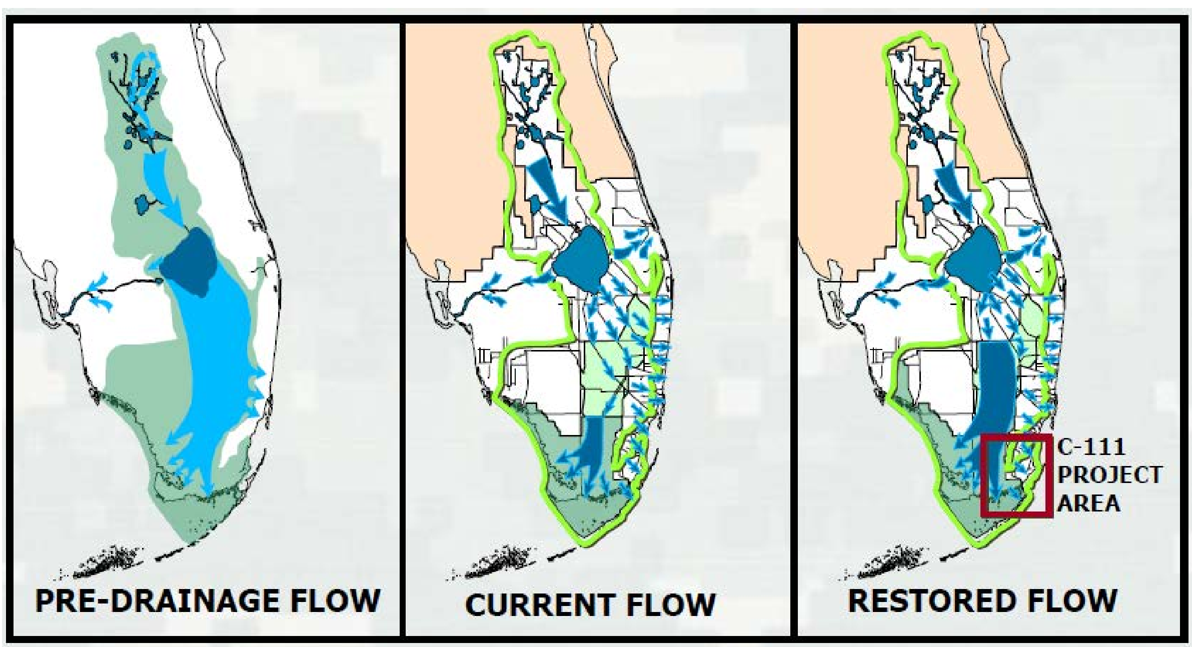

Figure 1 Map showing historic and current flows through the Greater Everglades Ecosystem, as well as planned restored flows under CERP and the location of the C-111 project.

The project then divided the remaining northern sawgrass and wet prairie west of this levee into conservation areas, separated by levees, designed primarily for water supply and flood control, with some provision for wildlife habitat and recreation (EAA and WCA areas) (National Research Council, 2003). Additional hydrological alteration occurred on the eastern boundary of the park with the construction of the Everglades National Park-South Dade Conveyance System.

Meanwhile, the added protection afforded by the perimeter levee on the south end of Lake Okeechobee and the conservation areas began attracting large-scale agriculture to east of the perimeter levee in Palm Beach, Broward, and Miami-Dade Counties (National Research Council, 2003). Consequently, the Corps plan called for installing a major levee and a grid of canals to protect lands east of the park and to carry water from south Dade, Homestead, and Florida City into Biscayne Bay, Florida Bay, and Barnes Sound. The National Park Service requested that water drained from the Taylor Slough headwaters be directed to the slough rather than routed to Barnes Sound via Canal 111 (C-111). Ultimately, a gate was installed and minimum monthly flows were established for Taylor Slough. However, since completion of the system in 1983, water levels and delivery patterns have been a source of controversy between the park, Dade County, the South Florida Water Management District, and the Corps.

Despite a minimum flow plan established by Congress in 1970, and the initiation of the Modified Water Deliveries project under the 1989 Everglades Expansion and Protection Act, flows into the Everglades remained insufficient to sustain the ecosystem, and created areas that were either too wet or too dry to sustain native habitat and species. The Comprehensive Everglades Restoration Plan, approved by Congress in 2000 (WRDA 2000), is a $10.5 billion, more than 30-year multi-agency project to restore the ecologically correct quantity, quality, timing and distribution of freshwater through the Everglades while distributing water for urban, agricultural and environmental purposes.

1.2 The C-111 Spreader Canal Western Project

The C-111 Spreader Canal Western Project is one of 68 CERP component projects. The C-111 Canal is the southernmost canal of the C&SF system. It provides flood protection and drainage for agricultural areas west and south of Homestead. However, significant quantities of water flowing into Taylor Slough seeps into the canal, where it flows east towards Biscayne Bay instead of southwest through Taylor Slough/ENP and into Florida Bay. This results in poor ecosystem health in both Taylor Slough and Florida Bay. In Taylor Slough, these water diversions have led to reduced hydroperiods, altered hydropatterns, and disruption of natural wetting and drying cycles, while in Florida Bay unnatural inflows and increased salinities have occurred.

Seepage reduction from Taylor Slough into the C-111 Canal has been the subject of a series of three projects: from the north, the Modified Water Deliveries Project, the C-111 South Dade Project, and the C-111 Spreader Canal Western Project. Sea level rise impacts on the Spreader Canal project is the focus of this analysis. The restoration benefits projected for the Spreader Canal project are associated with the rehydration of freshwater wetlands and reduced salinity conditions in nearshore areas downstream of Taylor Slough.

The C-111 Spreader project includes a number of features that together create a hydraulic ridge along the eastern edge of ENP to prevent subsurface flows from exiting the park via the C-111 canal (Figure 2 and Figure 3). Project features include weirs in the Frog Pond Detention Area and pumps moving water from the C-111 canal into both Frog Pond and adjacent Aerojet Canal. This allows water to infiltrate and saturate the soil under both features, effectively creating a hydraulic wall that reduces near-surface groundwater flow from Taylor Slough to the C-111 Canal.

Additional features include gated structures and pumps, and operational changes in other area canals, as well as plugs in the C-110 canal, all of which serve to keep groundwater levels higher in the wetland areas southeast of Homestead and Florida City.

The C-111 Spreader project area is located close to sea level in a low-relief landscape within the reach of current estimates for increases in mean sea level, and within the reach of storm surges under future climate conditions at projected higher future sea levels. Consequently, the project was of interest to the Responses to Climate Change program as a location to pilot recently-developed sea level guidance.

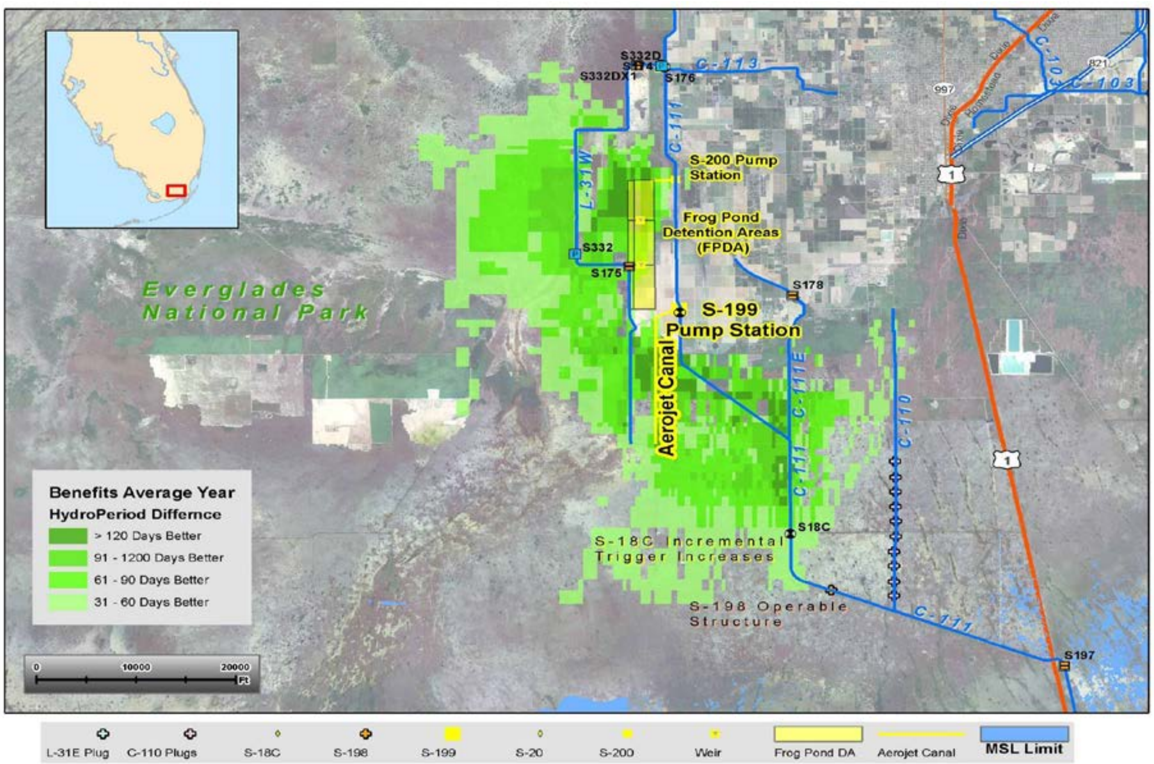

Figure 2 Map showing C-111 Spreader Western Project features.

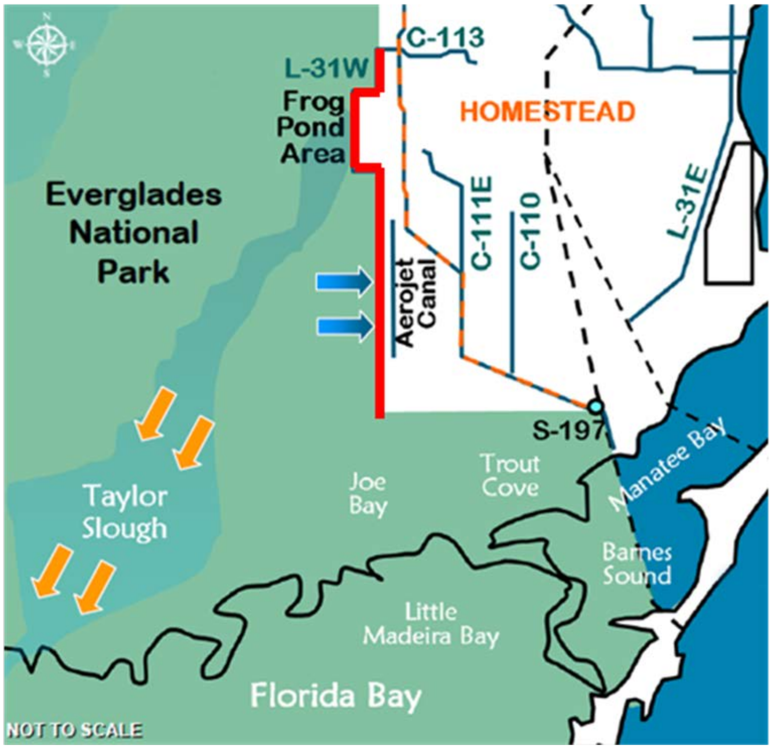

Figure 3 Map of the project area showing the approximate location of the hydraulic ridge (red line), with current seepage in blue and historical/desired water flow in orange.

1.3 Responses to Climate Change Program Adaptation Pilot Studies

The Responses to Climate Change (RCC) Program was started in FY2010 with the objective to develop and implement practical, nationally consistent, and cost-effective policies, methods, and approaches for effective adaptation of USACE projects, systems and programs to climate change (Darcy 2011). The Institute for Water Resources (IWR) was the logical place for this program given its history of involvement in climate change work.

The RCC Adaptation Pilot Studies Program seeks to implement a flexible framework for adaptation at the project scale and to increase understanding of how to prepare for climate change adaptation planning and implementation (Darcy 2011). Climate change adaptation pilot studies span the project life cycle and USACE business lines in river basins, coastal regions, and ecosystem projects. The lessons learned from these projects will help USACE to mainstream climate change adaptation, improve vulnerability assessment methods, develop an adaptive management strategy for climate change and variability, and improve water resources management and planning methodologies (Darcy 2011).

The USACE Responses to Climate Change (RCC) Pilot Program is designed to improve knowledge of climate change impacts and adaptation across all levels within USACE, from headquarters to the districts. They are also designed to foster communication between USACE and other Federal agencies to help guide the production of actionable science, or the collection of scientific information that is of use to planners and other decision-makers. Most of the work for this pilot study was conducted in FY2010, making it one of the earliest studies to be completed.

1.4 USACE Sea Level Rise Guidance

This project was conducted in Fall 2009, and followed the guidance available in EC 1165-2-211, Water Resources Policies and Authorities Incorporating Sea-Level Change Considerations in Civil Works Programs.

Under this guidance, planners are required to consider the impacts of sea level rise on proposed projects during the plan formulation process. Three degrees of sea level rise must be considered:

- The historic rate based on the nearest tide gauge is considered to be the "low" rate of sea level rise, since under a warming climate the rate of sea level rise should be the same or greater than the historic value. The use of observational data automatically adjusts the global rate of rise for local factors, such as subsidence, isostatic rebound, and other factors.

- The intermediate rate of sea level rise is taken to be Curve I as defined by the National Research Council's 1987 report, Responding to Changes in Sea Level: Engineering Implications. This curve must be modified to account for the current local sea level rise and adjusted based on the starting year (calculated from when the project is completed). The necessary equations can be found in ED 1165-2-211.

- The high rate of sea level rise is taken to be Curve III as defined by the National Research Council's 1987 report. This curve must be modified to account for the current local sea level rise and adjusted based on the starting year (calculated from when the project is completed). The necessary equations can be found in ED 1165-2-211.

The effects of sea level rise must be evaluated at 20, 50 and 100 years following project completion.

Since this project was completed, USACE sea level rise guidance has been revised. Current guidance is proved by ER 1100-2-8162, Incorporating Sea Level Change in Civil Works Programs (31 December 2013). This guidance continues to rely on the same methods originally outlined in EC 1165-2-211, and points users to additional resources for this issue. The USACE has also created an online sea level rise calculator to provide repeatable analytical results across the nation; this is available at http://www.corpsclimate.us/ccaceslcurves.cfm. Additional guidance for incorporating climate change into the USACE Civil Works planning process can be found in ETL 1100-2-1, Procedures to Evaluate Sea Level Change: Impacts, Responses and Adaptation. This guidance, published in 2014, incorporates an appendix specifically addressing ecosystem restoration projects, based in part on the lessons learned from this pilot project.

2 - Calculation of Sea Level Rise for the C-111 Project Area

Following guidance, the C-111 Spreader RCC Project considered three degrees of sea level rise in the project area. The historic rate of sea level rise was estimated from NOAA Key West tide station as 2.24 mm/yr. The intermediate and high rates were estimated based on the NRC I and III curves. The study assumed that the project would be completed in 2012. The study estimated sea level rise in 5-year increments for 100 years following project completion (Table 1 and Figure 4). By 2112, sea level rise is in the project area is anticipated to range from 8.8 to 68.8 inches (Figure 5, Figure 6 and Figure 7).

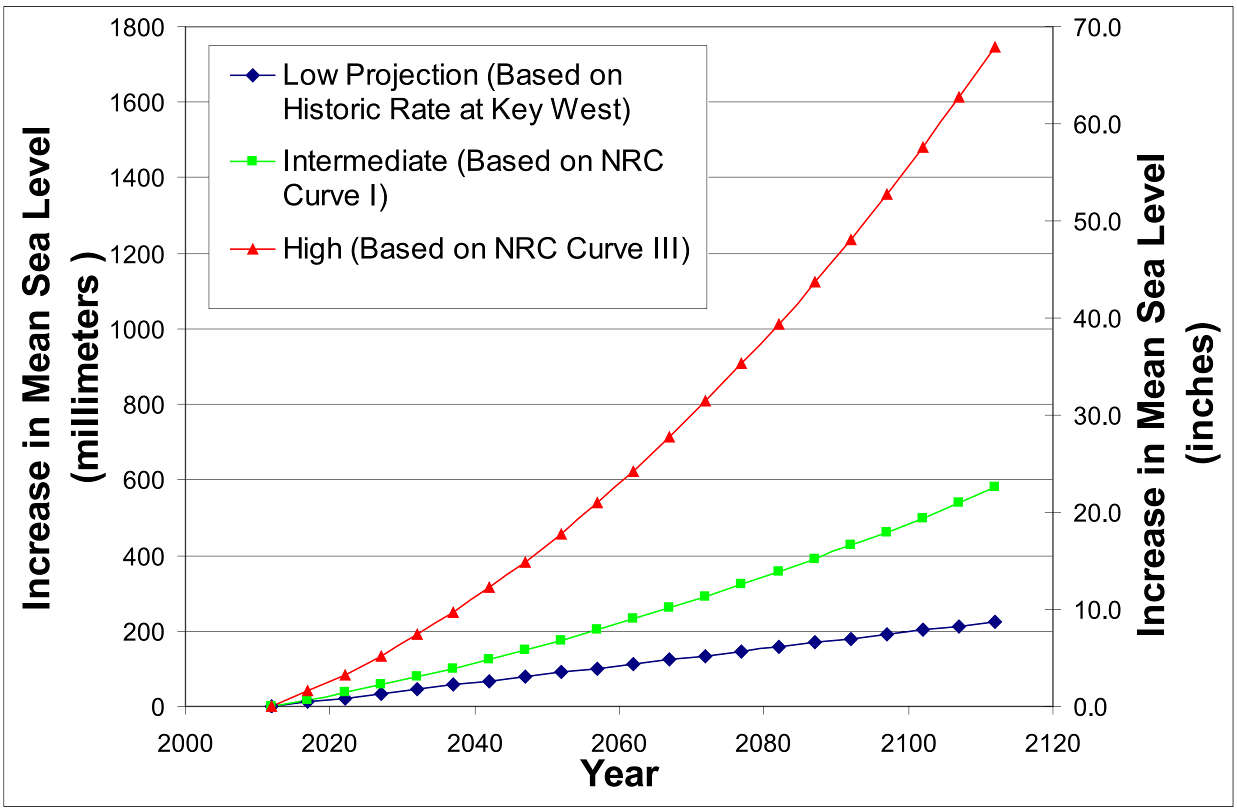

Figure 4 Projected sea level rise at C-111 spreader canal (assumes construction completed in 2012).

Table 1 Sea level rise at 5 year intervals for low, intermediate, and high projections (20, 50 and 100 years post-completion are shaded).

Year of Analysis	t_2 (years)	Low Projection (Based on Historic Rate at Key West) (mm)	Intermediate (Based on NRC Curve I) (mm)	High (Based on NRC Curve III) (mm)	Low Projection (Based on Historic Rate) (inches)	Intermediate (Based on NRC Curve I) (inches)	High (Based on NRC Curve III) (inches)
2012	26	0	0	0	0.0	0.0	0.0
2017	31	11	18	40	0.4	0.7	1.6
2022	36	22	37	84	0.9	1.4	3.3
2027	41	34	57	134	1.3	2.2	5.3
2032	46	45	78	189	1.8	3.1	7.4
2037	51	56	100	248	2.2	4.0	9.8
2042	56	67	124	313	2.6	4.9	12.3
2047	61	78	149	383	3.1	5.9	15.1
2052	66	90	175	458	3.5	6.9	18.0
2057	71	101	202	538	4.0	8.0	21.2
2062	76	112	230	623	4.4	9.1	24.5
2067	81	123	260	712	4.9	10.2	28.0
2072	86	134	291	807	5.3	11.4	31.8
2077	91	146	322	907	5.7	12.7	35.7
2082	96	157	356	1012	6.2	14.0	39.9
2087	101	168	390	1122	6.6	15.3	44.2
2092	106	179	425	1237	7.1	16.7	48.7
2097	111	190	462	1357	7.5	18.2	53.4
2102	116	202	500	1482	7.9	19.7	58.4
2107	121	213	539	1612	8.4	21.2	63.5
2112	126	224	579	1748	8.8	22.8	68.8

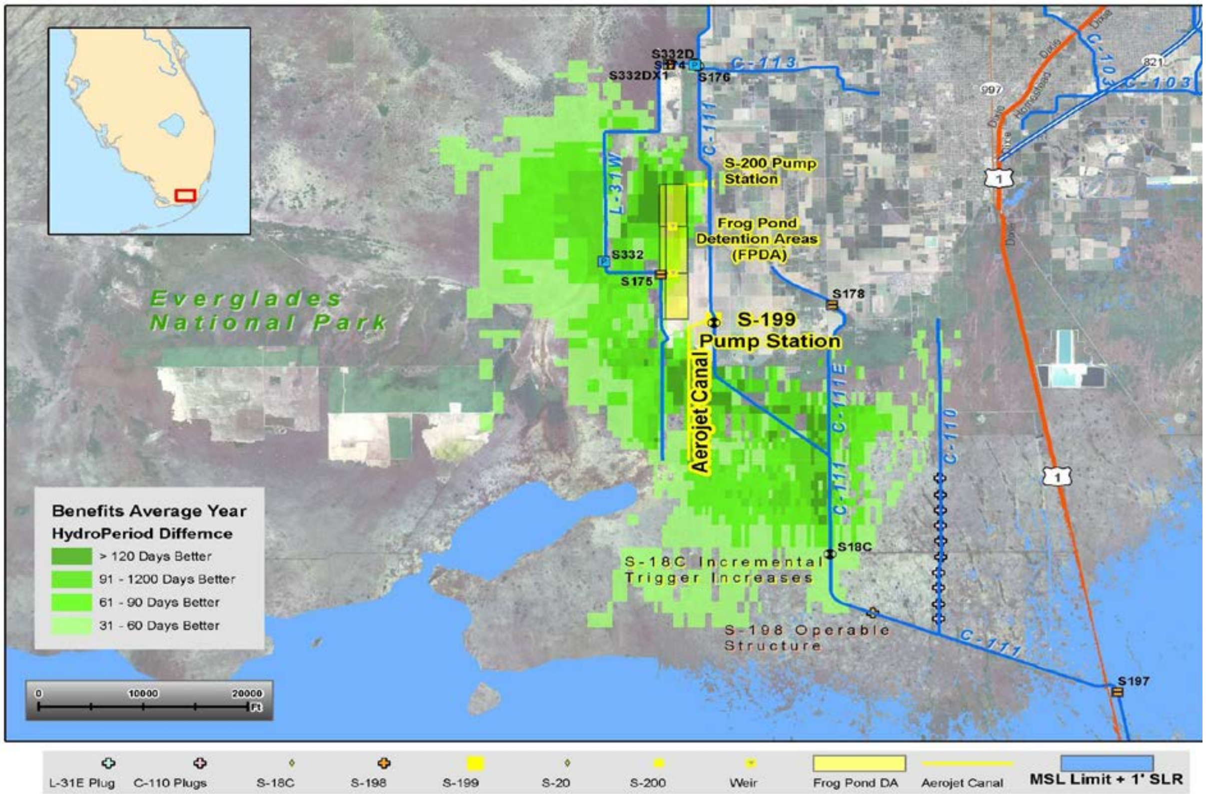

Figure 5 C-111 Spreader project area with 12" of sea level rise.

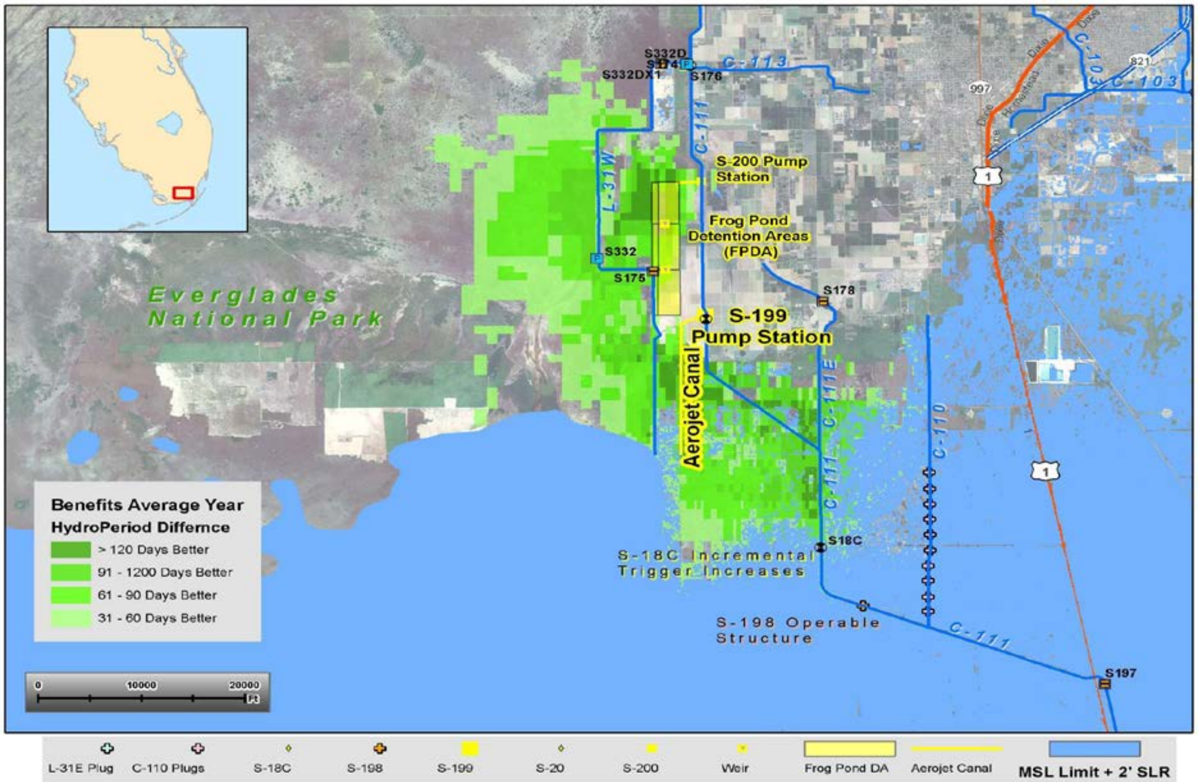

Figure 6 The C-111 Spreader project area with 24" of sea level rise.

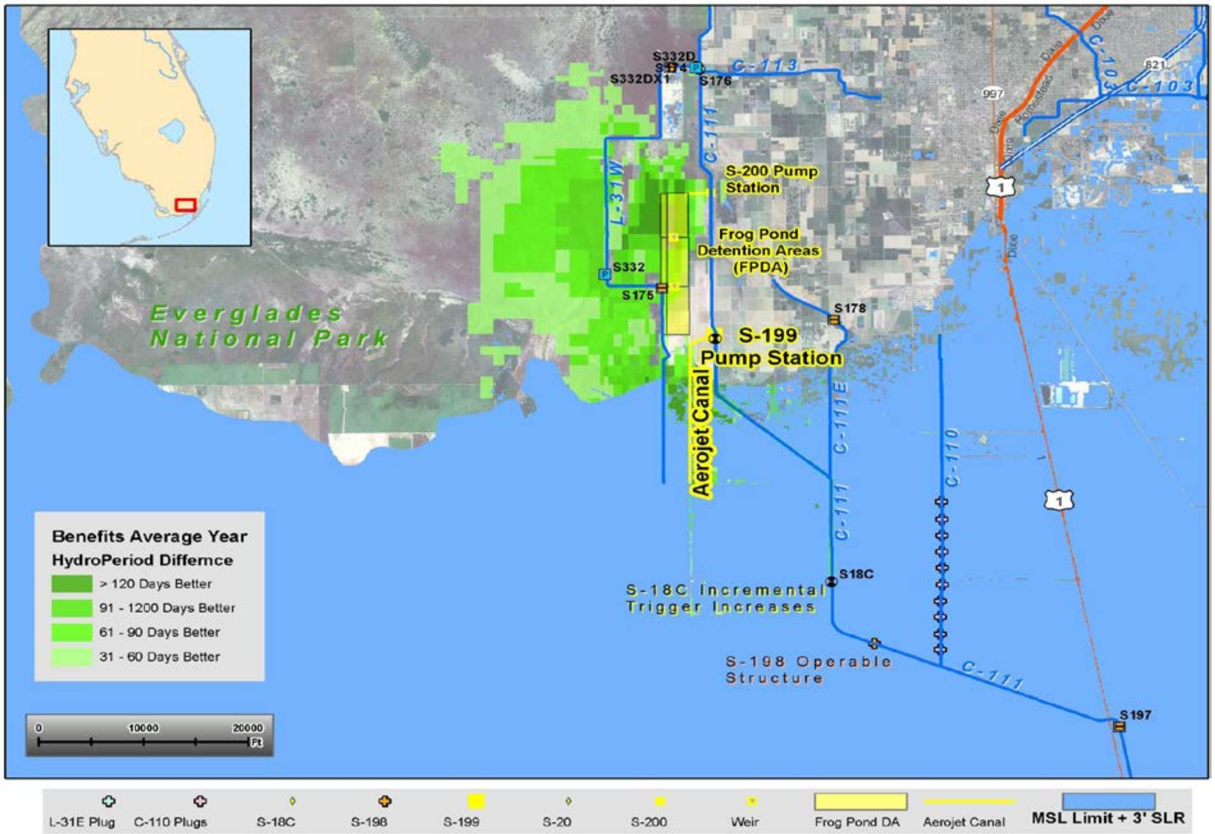

Figure 7 The C-111 Spreader project area with 36" of sea level rise.

The ecological benefits associated with this project are related to the enhancement of freshwater wetland hydroperiod in and around Taylor Slough and the improvement (reduction) in salinity conditions in the nearshore areas downstream of Taylor Slough. To assist in the evaluation of the likely effects of sea level rise on project benefits, the areas where the freshwater rehydration benefits are expected to occur were projected onto flood prediction maps generated under different MSL conditions. The mapping of the likely freshwater wetland benefits was created using difference mapping techniques that were generated using the groundwater stage output from the future without project scenario and the selected plan scenario. For freshwater wetland related project benefits, the degree to which the flooded area covers the benefitted zone under the "wet" condition simulation scenario was used as an indication of how these benefits are likely to be impacted by sea level rise.

As with the predictions of future rates of sea level rise, there is uncertainty in the estimation of effects to project related ecosystem benefits due to the accuracy and reliability of the datasets used in this analysis. The mean sea level flood prediction maps used in this analysis are based upon topographic data that is known to be accurate only to within plus or minus 0.5 ft. The land elevation is assumed to be static over the 20, 50, and 100 year periods; however, topographic change is likely to occur as a result of sea level rise and other natural processes. In addition to these sources of topographic uncertainty, the benefitted area mapping is based upon ModBranch model output that has a groundwater stage prediction accuracy estimated at 0.5 ft. Despite these limitations and inherent uncertainties, the analysis is presented as it is the most reliable information available at this time.

Figure 8 Freshwater prairie, Taylor Slough.

Sea Level Rise Impacts

As sea levels rise, progressive inundation of larger portions of the ENP and southern Miami-Dade County is anticipated. This is likely to be accompanied by the inland migration of the coastal mangrove ecosystems (following the brackish water zone), expansion of white zone (degraded) habitat, and progressive decrease in the area of freshwater sawgrass wetland. The rate and magnitude of these changes is closely tied to the pace of sea level rise over the 21st Century. The effects of these changes on water quality in Florida Bay are outside of this study.

Historic sheetflow conditions prior to drainage created pooling of freshwater upstream from mangrove estuaries and resulted in prolonged freshwater flows into the estuaries. The canal network has resulted in the reduction of freshwater volume and duration, which in turn has shortened the hydroperiod, reduced freshwater pooling along the sawgrass/mangrove ecotone (the transition area between the sawgrass and mangrove biomes), and disrupted sheetflow. Florida Bay became more saline due to the loss of freshwater inputs from Taylor Slough as water management features (drainage canals) were constructed in Southern Miami-Dade County. The existing habitats in the project area are shown in Figure 9 and described in Table 2.

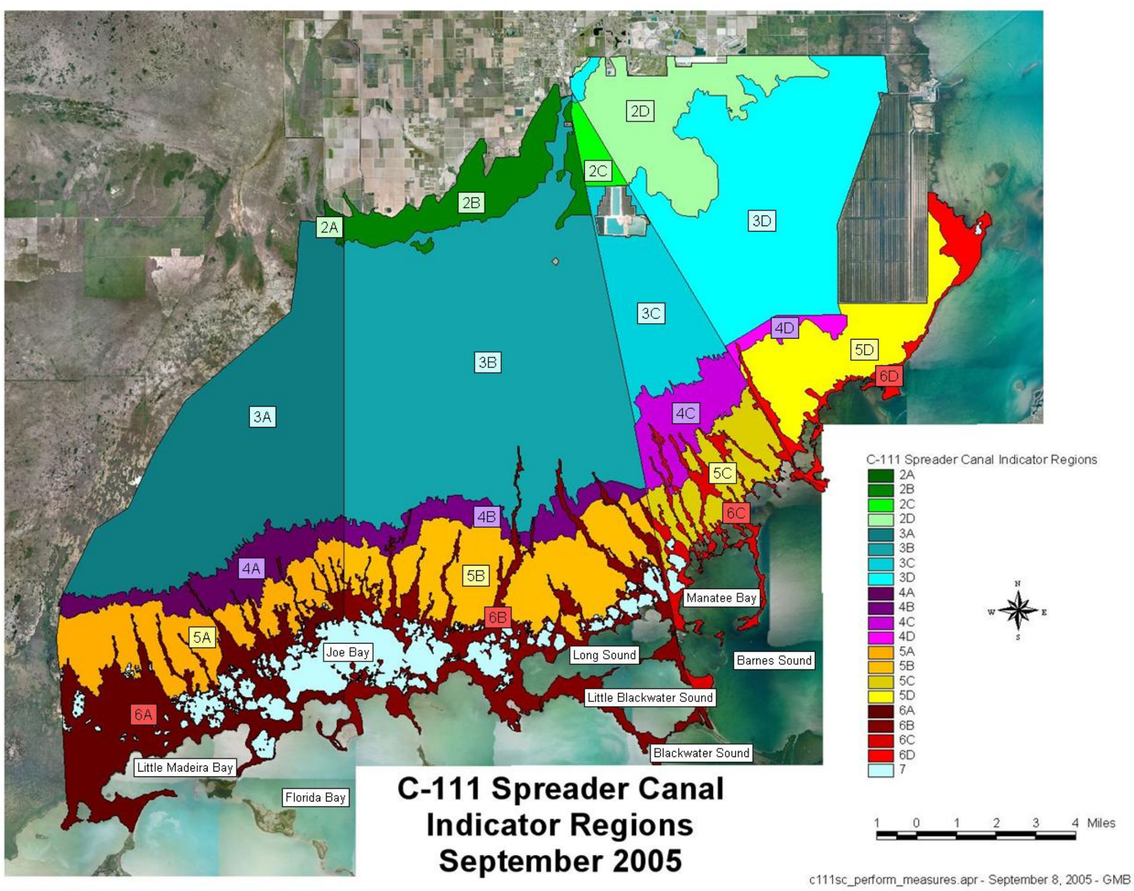

Figure 9 Habitat map of C-111 spreader canal project area, where 2=shrubs, 3=sawgrass wetlands; 4 and 6 = mangrove forests; and 5 = white (degraded) zone.

Table 2 Vegetation and hydroperiod for habitat zones.

Zone	Hydroperiod	Existing Landscape	Existing Vegetation and Hydroperiod Response
2	130-180 days – hydroperiod range for the dry phase that should support muhly-mixed graminoids	Shrub dominated forested wetland	Freshwater wetland habitat. Brazilian pepper (*Schinus terebinthifolius*), Australian pine (*Casuarina* spp.), dahoon holly (*Ilex cassine*), swamp bay (*Persea palustris*), sweet bay (*Magnolia virginiana*), willow (*Salix caroliniana*), and sawgrass (*Cladium jamaicense*). Discontinuous hydroperiod controls overall plant distribution.
3	150-330 days - hydroperiod range.	Sawgrass	Freshwater wetland habitat. Sawgrass, muhly grass (*Muhlenbergia capillaris*), swamp bay, dahoon holly, wax myrtle (*Myrica cerifera*), willow, and cocoplum (*Chrysobalanus icaco*), sweet bay, myrsine (*Rapanea guianensis*), bald cypress (*Taxodium distichum*), and pond apple *(Annona glabra*). Continuous hydroperiod is more relevant to aquatic fauna productivity.
4	240-330 days - hydroperiod range.	Mixed graminoid with mangroves	Sawgrass, swamp bay, dahoon holly, wax myrtle, cocoplum, myrsine, poisonwood (*Metopium toxiferum*), buttonwood (*Conocarpus erectus*), red mangrove (*Rhizophora mangle*), stoppers (*Eugenia* spp.), spicewood (*Calyptranthes pallens*), and cocoplum
5	240-330 days - hydroperiod range.	White zone ecotone	Salt tolerant Dwarf red mangroves, sparse graminoids. Discontinuous hydroperiod controls plant distribution.
6	240-330 days - hydroperiod range.	Coastal forest	Red mangrove, white mangrove (*Laguncularia racemosa*), Brazilian pepper , Australian pine, wax myrtle,, poisonwood,, buttonwood, spicewood, myrsine, stoppers, white indigo berry (*Randia aculeata*). Desired salinities are 5-15 ppt necessary to sustain oligohaline and mesohaline conditions.

It is anticipated that restoration of pre-drainage freshwater flow volume, distribution, and duration in Taylor Slough will prolong the pooling of freshwater, and increase volume and duration of freshwater to the estuaries (Davis et al. 2005). Additional freshwater through Taylor Slough will decrease salinity, leading to the increase of growth and survival of estuarine species. One expectation of the restoration in this area is that changing the patterns of freshwater flows going into Florida Bay will drive the seagrass community and trophic web toward the pre-drainage condition (Rudnick et al. 2005).

The effect of sea level rise on C-111 basin habitat will vary depending upon the location and elevation of the affected lands. Given the region's extremely low elevation and low relief, it is anticipated that sea level rise will have widespread impacts to habitats in the southern portion of Taylor Slough and throughout the southern Everglades. As sea level comes up, the white zone habitat and mangrove forest will move north into areas currently dominated by sawgrass; nearshore shallow estuarine habitat in Florida Bay that is targeted for salinity improvement by this project will also move north. Peat soils in the southern portion of Taylor Slough may decompose and disappear as saltwater intrudes into the former freshwater sawgrass marsh areas. The rate of future sea level rise will impact how quickly these changes occur and how extensive these changes are in 20, 50 and 100 years' time.

Sea level rise is expected to modify the patterns of connectivity through coastal wetlands and create increased sediment loads in tidal creeks (Davis et al. 2005). This deposition may increase if more extreme weather events become more common or stronger as climate warms. If sea level rise is accompanied by an increase in tropical storm intensity and frequency, the rate of soil accumulation may increase and partially offset higher mean sea level conditions. For example, Hurricane Wilma resulted in approximately 5 cm accumulation of sediment deposits in the mangrove zones in 2005 (Whelan, 2009).

Under higher rates of sea level rise, the increase in groundwater stages and in surface water depths will result in a loss of flood protection for the area. Changes to the open/close operating criteria at canal structures may be instituted as water managers attempt to counteract the effects of sea level rise on flood protection and salinity control. The sea level rise related increase of groundwater stage in the northern part of the project area could provide increased hydration to the area to the extent that the water management practices are not significantly modified in an effort to continue to provide flood protection to lands east of the L-31N and C-111 canal alignments. With no change to water management operations, lands to the east of the C-111 canal that are still farmland will likely be abandoned and revert to freshwater wetland habitat since farming is likely to be uneconomical in the face of increased flooding. This is an observed phenomena in the nearby Model Lands where acreage previously farmed in the 1940s to 1960s has reverted to wetlands due to sea level rise related increased flooding among other factors.

The estimation of the effect of sea level rise on the salinity benefits resulting from this project is less quantitative than that done for the freshwater wetland benefits. Given the gentle slope of Taylor Slough and other areas of the southern glades, sea level rise is expected to result in the translocation of estuarine nursery habitat northward as MSL increases. In Taylor Slough, man-made boundaries such as a levee or canal that would limit the northward march of the estuarine environment are presently many miles from the existing shoreline. Under the lower to moderate sea level rise projections, it is possible that sea level rise will actually provide a greater area of estuarine habitat than that presently. There is some uncertainty in the prediction of viable estuarine habitat since it depends upon local scale topography and future changes to the landscape resulting from peat soil decomposition and storm event related sediment deposition.

Finally, sea level rise impacts to ecosystems may depend on the amount of rise relative to tidal range. Within the project area, the tidal range (elevation difference between mean higher high water (MHHW) and mean lower low water (MLLW)) is approximately 2 feet. A 1 foot increase in mean sea level will shift 50% of the existing tidal ecosystem one foot upslope. Given the shallow slopes in the study area, this change would result in an approximately 30,000 foot (6 mile) shift (Figure 10), a significant change in the geographic distribution of these ecosystems. If sea level rises occurs slowly, over many decades as projected under the lower sea level rise curves, the existing ecosystem may shift without significant losses or changes. However, if 1 ft of sea level rise were to happen in only a few decades, as could happen in the last part of this century under the high rate of sea level rise scenario, it is possible that not all species could adapt to such rapid change. As a consequence, the tidal zone and near shore shallow marine ecosystems may look and function differently in the future. Although this project assumed the lateral migration of intact ecosystems, future projects should explore whether ecosystems will remain intact and continue to perform their vital functions as sea levels rise. This is something should be explored in planning for future adaptation needs, and it may be an important consideration in some other project areas especially if dealing with an endangered or threatened species that is sensitive to tidal zone changes.

Using the methodology described above, qualitative assessments of the sea level rise impact to project benefits are discussed for three sea level rise projections at three different points in time.

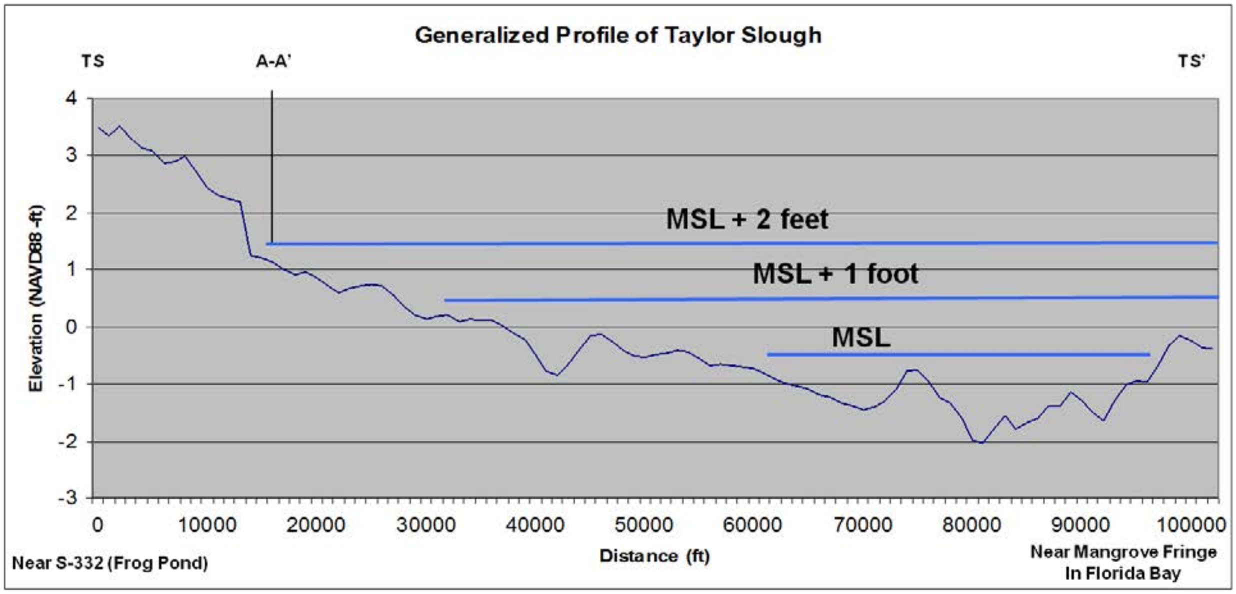

Figure 10 Generalized profile of Taylor Slough, showing the effects of sea level rise.

3.1 Projected Effects of Sea Level Rise at 20 Years Post-Construction

At 20 years post-construction, the low projection for sea level rise is 1.8 inches, the intermediate projection is 3.1 inches, and the high projection is 7.4 inches. The location of the project area relative to the flood lines for current mean sea level (MSL) is shown in Figure 3 and for 12 inches of sea level rise (MSL+1 ft) in Figure 5. At 20 years post-construction, a linear interpolation between the shorelines on these two maps shows that the low and moderate projections for sea level rise should result in no adverse effect on the benefits predicted for freshwater wetland rehydration. The quantity of water available for diversion by the project features should not change significantly so related benefits should be achievable.

The high rate of sea level rise, resulting in a rise of 7.4 inches above current mean sea level, will result in a reduction in project benefits due to saltwater encroachment on the freshwater benefit area. A comparison of location of the flood lines in Figure 5 with the habitats mapped in Figure 9 suggests that approximately 10% of the sawgrass wetlands likely will convert to mangrove, white zone, and shallow estuarine habitat (Table 3). However, relative to the future without condition, the project will likely significantly reduce the rate of conversion of sawgrass habitat to transitional and saltwater habitat through the additional freshwater that will be diverted into Taylor Slough.

The impact of sea level rise on salinity benefits in the nearshore zone over the next 20 years is expected to be minimal under all three projections as the zone of optimal salinity conditions is anticipated to move upland (northward) in response. Under the low sea level rise projection, it is likely that the rate of sediment deposition in the nearshore, mudbank, and mangrove areas will match sea level rise resulting in minimal change in average embayment depth. Under the moderate and high sea level rise projections, some change in the total area where salinity conditions are optimal for some mesohaline and oligohaline species is expected. However, given the gentle slope of the topography of Taylor Slough and the lack of manmade barriers such as levees or canals, it is unlikely that sea level rise will result in the complete loss of mesohaline and oligohaline areas under any scenario in 20 years. At the higher sea level rise estimate, some reduction in the severity and duration of hypersaline conditions in Barnes Sound, Manatee Bay, and Florida Bay proper is likely since the rate of exchange of bay water with ocean water is likely to increase as the existing island barriers to this exchange become submerged.

Table 3 The effects on restoration benefits after 20 years of sea level rise.

Increase in Mean Sea Level	Freshwater Wetland Rehydration	Nearshore Salinity Conditions
Low (1.8 inches)	No Effect	No Effect
Intermediate (3.1 inches)	No Effect	Minimal Location Shift
High (7.4 inches)	Minor (<10%)	Location Shift

3.2 Projected Effects of Sea Level Rise at 50 Years Post-Construction

At 50 years post-construction, the low projection for sea level rise is 4.4 inches, the intermediate projection is 9.1 inches, and the high projection is 24.5 inches (Table 1). Interpolation between the current shoreline position (Figure 3) and the shoreline location with 12 inches of sea level rise (Figure 5) suggests that project-related freshwater wetland benefits are unlikely to be affected by sea level rise in 50 years at the lowest projected rate. Comparison of these same maps, and similar to the 7.4 inch rise at 20 years post-construction, the intermediate rate of sea level rise of 9 inches in 50 years is expected to result in a reduction of approximately 10% of freshwater wetlands identified as benefiting from the C-111 Spreader Canal Western Project. However, under the higher rate of sea level rise, a comparison of the habitat map (Figure 9) with the mapped extent of sea level rise (Figure 6) indicates a reduction of approximately 33% in the area of the freshwater wetlands identified as benefiting from the project (Table 4).

Under the lowest projected rise, at 50 years the MSL flood line would not be directly adjacent to an existing man-made canal or levee and there would be no natural topography that limits the areal expanse of shallow estuarine habitat areas. Since there is minimal change to the size of the estuarine habitat zone, no significant reduction in project-related salinity benefits are anticipated for a sea level rise of 4.4 inches in 50 years.

Under the intermediate and high sea level rise projections, lands directly adjacent to the C-111 canal would be flooded by the rising sea. Consequently, the area available for estuarine habitat under these scenarios may be reduced in areas where the C-111 canal is parallel to the shoreline but not where it is perpendicular to the shoreline. However, since the C-111 canal is generally perpendicular to the shoreline and flooding would likely occur on both sides of the canal, any reductions in area suitable for estuarine habitat is likely to be small. Consequently, there are no expected reductions of saltwater-related project benefits. Under the moderate and high estimates of sea level rise at 50 years, it is likely that there will be a reduction of hypersaline conditions in Florida Bay as exchange with ocean water will increase over present volumes. The related reduction of hypersaline conditions in Barnes Sound and Manatee Bay should enhance nearshore habitat in those areas.

Table 4 The effects on restoration benefits after 50 years of sea level rise.

Increase in Mean Sea Level	Freshwater Wetland Coverage in Taylor Slough	Nearshore Salinity Conditions
Low (4.4 inches)	Not Significant	Not Significant
Intermediate (9.1 in)	Minor (10% reduction)	Location Shift
High (24.5 inches)	Significant (33% reduction)	Location Shift

3.3 Projected Effect of Sea Level Rise at 100 years Post-Construction

Analysis of the effect of sea level rise on projects at 100 years post-construction is a requirement of EC 1165-2-211; it recognizes that many USACE projects continue to perform their functions long past the end of their official use-life (as many western U.S. dams attest). The project life cycle used in USACE planning for design, and for calculating anticipated benefits and costs, is 50 years. Thus CERP benefits were only analyzed out to 50 years post-construction. Any benefits accrued after 50 years, whether or not lost due to sea level rise, were not used in the cost-benefit analysis used to justify the project during planning.

At 100 years post-construction, the low projection for sea level rise is 8.8 inches, the intermediate projection is 22.8 inches, and the high projection is 68.8 inches (Table 1). The total rise under the low projection (8.8 inches) will have comparable impacts to the intermediate rise at 50 years (9.1 inches) and the high rise at 20 years (7.4 inches): approximately 10% of the freshwater wetlands identified as benefiting from the project will be impacted. The total rise at 100 years under the intermediate curve (22.8 inches) is comparable to the total rise at 50 years for the higher rate (24.5 inches), and there effects are likely to be similar: approximately 33% of the freshwater wetlands identified as benefiting from the project are likely to be impacted by sea level rise under the moderate projection estimate of 22.8 inches in 100 years. However, if sea level rises at the highest rate, reaching 68.8 inches (>5 ft) in 100 years, all of the freshwater benefits resulting from the project will be lost (Table 5).

Under the low projection at 100 years, the MSL flood line is not directly adjacent to an existing man-made canal or levee and there is no natural topography that limits the areal expanse of shallow estuarine habitat areas. Under the intermediate sea level rise projections, lands directly adjacent to the C-111 canal would be flooded by the rising sea. Consequently, the area available for estuarine habitat under these scenarios may be reduced in areas where the C-111 canal is parallel to the shoreline but not where it is perpendicular to the shoreline. However, since the C-111 canal is generally perpendicular to the shoreline and flooding would likely occur on both sides of the canal, any reductions in area suitable for estuarine habitat is likely to be small.

Under the highest rate of sea level rise, at 100 years post-construction there is likely to be a significant reduction in the area available for estuarine habitat (Figure 7); however, this will depend upon the number and placement of structural flood risk management measures (canals, levees) that may limit sea level encroachment on developed and agricultural areas. Consequently, under the highest rate of sea level rise, there may be a reduction in the total extent of nearshore shallow areas suitable for estuarine habitat. Under the high projected sea level rise, salinity conditions within Florida Bay would increase to levels typical of marine systems as the average depth of the bay would more than double from over 1.0 meter to 3 meters, resulting in the submergence of many of the eastern Florida Key islands that currently serve as a barrier to ocean exchange.

Table 5 The effects on restoration benefits after 100 years of sea level rise.

Increase in Mean Sea Level	**Freshwater Wetland Rehydration**	**Nearshore Salinity Conditions**
Low (8.8 inches)	Minor (10% reduction)	Location shift
Intermediate (22.8 inches)	Significant (33% reduction)	Location Shift
High (68.8 inches)	All lost	Location Shift and losses

4 - Resilient Design in the Face of Sea Level Rise

There is significant uncertainty around the rate but not the direction of sea level rise over the next 50 to 100 years. To reduce the risk associated with implementing the project, flexibility in the design and operation of features can be incorporated into the project during the planning phases. Also features planned and operated for one purpose can be repurposed as sea level rise begins to affect water management needs into the future. Thus, the existing and planned infrastructure of the CS&F and CERP projects are likely to prove resilient if sea levels rise at the low and intermediate rates.

For example, the planned S-198 structure that is located half way between S-18C and S-197 (see Figure 3) is designed to primarily assist in rehydrating adjacent wetlands by holding the groundwater stage slightly higher than currently. As sea level rise begins to impact mean sea level, the ability of the S-197 structure to provide salinity control benefits will diminish. At this point, the S-198 structure will then begin to provide salinity control benefits by limiting northward migration of the saltwater front within the C-111 canal. Similarly as sea level rise contributes to marginal decreases in the C-111 canal system's ability to provide flood protection due to increased tail water conditions at S-197 and S-18C as well as increased average groundwater stages, the project’s S-200 and S-199 pump stations can be used to assist in removing the marginal increase in flood flows from the C-111 canal. Increases in groundwater stage due to sea level rise could also be mitigated to some extent by using the two project pump stations to send more freshwater through Taylor Slough than would be available in the absence of sea level rise.

Figure 11 The Frog Pond detention area within the C-111 Spreader Canal Western Project area.

5 - Conclusions

This analysis looked at the effect of sea level rise on the benefits predicted for the selected alternative for the C-111 Spreader Canal Western Project. The results indicate that within the 50-year planning horizon, the freshwater wetland rehydration benefits attributed to the selected plan could be diminished as much as 33% under the highest sea level rise scenario. Benefit impact would be somewhat higher if the mean higher high water elevation controls habitat shift rather than the mean sea level line. Nearshore salinity benefits are not expected to be significantly impacted by the 50 year high sea level rise estimate. Limited impacts to project benefits were seen at the low and moderate sea level rise projections at 50-years. Though a similar analysis was not carried out for the remaining with-project alternatives; the results would be similar since all of the alternatives also focus on features located at the Frog Pond and Aerojet canal as does the selected plan. Given the similarity in location among the array of project alternatives, differential impacts of sea level rise would not contribute to distinguishing among the alternatives. Somewhere between 50 and 100 years post-construction, well beyond the 50-year planning horizon used to justify projects based on cost and benefit estimates, under the highest sea level rise scenario all project benefits would be lost. This potential loss does not negate the necessity of project construction: the habitats created and sustained by the C-111 Spreader Canal Western Project will be essential to the preservation of freshwater sawgrass wetlands and estuarine mangrove habitats, and associated plant and animal species, providing a bridge between where they are now and where they will be in 100 years' time.

Key lessons learned during this RCC Adaptation Pilot Study include:

- The sea level rise guidance employed in this study was straightforward to apply, and produced information that was helpful to decision makers wanting to understand potential future SLR impacts.
- More sophisticated evaluation tools are needed to better understand how sea level rise may impact surface water and groundwater conditions, erosion/sedimentation, and vegetation tolerance to shifts in salinity, wave action, and other factors.
- Climate change provides a strong incentive for accelerating ecosystem restoration projects. Healthy ecosystems are more resilient and probably better able to adapt to future changes.
- Recognize that without human barriers, coastal ecosystems would naturally shift locations based on drivers such as sea level change. Seek to sustain ecosystem diversity by providing opportunities for ecosystem shifting.
- Knowledge about climate change and related impacts is constantly growing, and should be integrated into future ongoing studies, implementation plans and monitoring.
- Ecosystem restoration planners should actively consider sea-level rise and potential hydrologic changes in system-wide planning and project prioritization.
- Design for flexibility anticipating future changes in temperature, precipitation & sea-level change.

- High priority research is needed to help understand potential impacts of climate change on natural ecosystems, and help develop better long term adaptation and sustainability strategies.
- Regional models must be modified or developed to evaluate potential climate change-related variations in rainfall, evapotranspiration and tropical storms.
- Local models with one foot topographic contours are needed for evaluation of potential sea level rise and salt water intrusion impacts in natural and developed coastal areas.

Figure 12 Florida Bay, a critical component of the Everglades ecosystem that is threatened by sea level rise.

6 - References

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