A GIS APPROACH TO PREDICT LOW AND EXTREME SEA LEVEL RISE SCENARIOS IN FLORIDA BY 2100

Investigating potential inundation of land uses, essential services, and the Coastal Construction Control Line (CCCL)

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Essential Services, Coastal Construction Control Line (CCCL)
ArcGIS, Clip, Batch Clip, Project, Kernel Density, Cluster

Abstract

This paper utilized GIS data to compare low (~0.3 m) and extreme (~2.4 m) predictions of sea level rise (SLR) at high tide in Florida by 2100. National Oceanic and Atmospheric Administration (NOAA) SLR predictions were clipped with Florida Land Use Cover, Forms, and Classification System (FLUCCS) land cover classifications, various essential services, and the Coastal Construction Control Line (CCCL). Geometry values for each land cover type and essential service inundated by SLR were calculated using Esri ArcGIS and results were saved in MS Excel. A series of maps were produced revealing a wide range of outcomes for inundation of various land uses, essential services, and the CCCL based on low to extreme scenarios of SLR across Florida. It was estimated between 4,482 sq km to 13,859 sq km of land in Florida could be inundated under high tide by 2100. Total land area lost to SLR in Florida will overwhelmingly be wetlands, which act as a natural physical barrier to SLR inundation of other land uses. However, the input data used in this research has several limitations, including the unpredictability associated with SLR projections. Additional research is needed to monitor the rate of SLR over time, effects of SLR on inland habitats, how governments and human migratory patterns are directing development into (or away from) highly vulnerable SLR areas, as well as *how* to integrate changes needed to solve wicked environmental problems in the Anthropocene.

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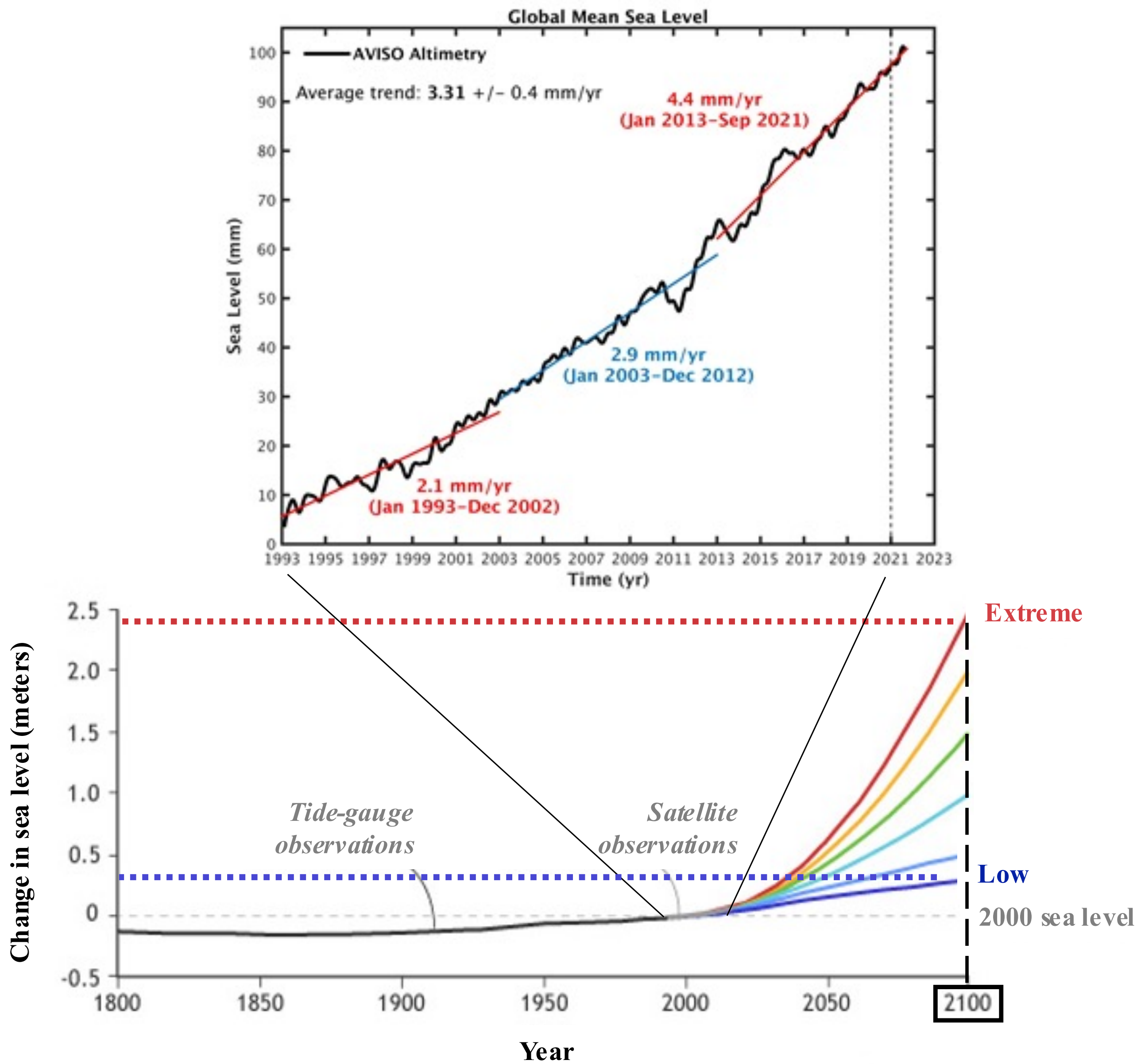
I. INTRODUCTION

In the current geological epoch, the Anthropocene, human activities, such as land use and land cover change, are responsible for abrupt and severe environmental changes (Rockström et al., 2009). While land use and land cover change has been crucial for human survival for thousands of years, its rate and intensity are more extreme now than before (Lu et al. 2016). Many of Earth's inter-connected biophysical subsystems and processes react in non-linear fashions that could have disastrous consequences for society if planetary boundaries are crossed (Rockström et al., 2009). This is alarming because numerous civilizations of the past have collapsed because of environmental problems (Ehrlich & Ehrlich, 2013), and rising sea level is expected to be among the most important impacts of anthropogenic climate change in the next century (Grinsted et al., 2009).

The recent upward trends of sea level rise (SLR), and the frequency and intensity of hurricanes and other extreme weather events, has been widely documented, as well as the increase in economic losses resulting from natural disasters (Estrada et al., 2015). Geological studies show sea levels have fluctuated all over the world throughout the distant past (Florida Oceans and Coastal Council, 2010). While SLR has been slowly occurring along Florida's coast for the last few thousand years (Maul & Martin, 1993), scientists have observed a persistent increase in the rate of SLR in recent decades since being measured and tracked using tide stations and high precision laser altimeter satellites (WMO, 2021). This increase in global mean sea level is mostly caused by accelerated melting of glaciers and ice sheets (WMO, 2021) and thermal expansion of ocean surface waters (Thomas, 1987). Additionally, it is predicted to increase between ~0.3 to ~2.4 meters (1 to 8 feet) above 2000 levels by 2100, as shown in Figure 1 (NOAA OceanService.gov, 2021).

Figure 1. Changes and predictions of global mean sea levels.
Top: Changes in global mean sea level (mm) from 1993-2023. *Image Source: WMO (2021)*
Bottom: Possible change in future sea levels (m) by 2100 for different greenhouse gas pathways.
Modified from Image Source: NOAA Climate.gov (2021) adapted from Sweet et al. (2017)



Millions of people face being displaced by SLR, forcing coastal communities to protect their shorelines from erosion (Nicholls, 2011). SLR both passively inundates low-lying coastal areas while also actively changes storm intensity, thus accelerating erosion in a feedback loop where ocean inundates what was previously land (Tralli et al., 2005). This is a crucial issue in Florida where the topography is relatively flat (median elevation = 21 m, interquartile range = 13-32 m) (NASA/METI/AIST/Japan Space systems, U.S./Japan ASTER Science Team, 2011) and almost none of the infrastructure was built to withstand significant SLR (Florida Oceans and Coastal Council, 2010). Substantial costs are associated with accommodating SLR, as $1.1B (40% of the national costs) has already been spent on beach nourishment projects in Florida between 1960 through 2007 (Kildow, 2008). Further, in October 2021, the World Meteorological Organization (WMO, 2021) reported that "extreme weather is the new norm," so it is expected that additional funding will continue to be needed to keep up with future ongoing beach renourishment projects.

Beach stabilization and nourishment projects along with the State's Coastal Construction Control Line (CCCL) permit program are helping counteract long-term erosion along Florida's coasts (Florida Oceans and Coastal Council, 2010; Dehring, 2006). The CCCL is a jurisdictional line that defines the landward extent of damages caused by a 100-year storm event based on scientific principles, engineering predictive models, surveys, and bathymetric data following methods of Rule 62B-33.024, Florida Administrative Code (Florida Department of Environmental Protection, 2017). The CCCL program plays a role in mitigating and regulating the structures and activities that result in beach erosion, dune destabilization and property damage (Florida Department of Environmental Protection, 2021). However, even with mitigation efforts there is expected to be an increase in impacts on coastal infrastructure, which remains a major issue associated with 15 of Florida's 20 major population centers located at low elevations near the shoreline (Florida Oceans and Coastal Council, 2010). While CCCL jurisdictional setbacks direct new proposed development away from shore based on a multiple of the annual average erosion rate (Deyle et al., 2007), there are currently no plans to adjust the CCCL accounting for changes to the annual erosion rate with SLR. Therefore, it is worth investigating where the CCCL could become inundated by different scenarios of SLR and if any spatial clustering of CCCL permits exists (Deyle et al., 2007).

Significance and Rationale

While many studies already exist that focus on SLR predictions at various scales from global to local (Nicholls, 2011), less is known about how the CCCL will be inundated under various SLR scenarios. It is critical to investigate where and to assess the extent that SLR is expected to displace different land uses, essential services, and the CCCL to help inform effective future land use planning decisions. When visualizing SLR, multiple scenarios (as opposed to a single scenario) should be presented for map users to clearly demonstrate the uncertainties associated with SLR processes (Kostelnick et al., 2009). Therefore, this paper investigates how both the low and extreme scenarios of SLR in Florida by 2100 may inundate the different land uses, essential services, and the CCCL.

Main Objective

The main objective is to examine differences in SLR predictions on land use, essential services, and the CCCL in Florida by 2100.

Specific Objectives

To gather publicly sourced GIS data from various academic research and government agencies (e.g. Florida Geographic Data Library (FGDL); National Oceanic and Atmospheric Administration (NOAA); Florida Department of Environmental Protection (FDEP)) and create a workflow and several maps of Florida that will be used to:

(1) Assess the extent that different land uses and essential services could be inundated based on predictions of low to extreme (~0.3 m (1 ft) to ~2.44 m (8 ft)) scenarios of SLR by 2100

(2) Identify where rising sea levels could inundate the CCCL, as well as if, and where, spatial clusters of CCCL permits exist

(3) Compare results to other studies in Florida, and identify future research needs and opportunities for GIS to improve predictions of SLR.

II. METHODOLOGY

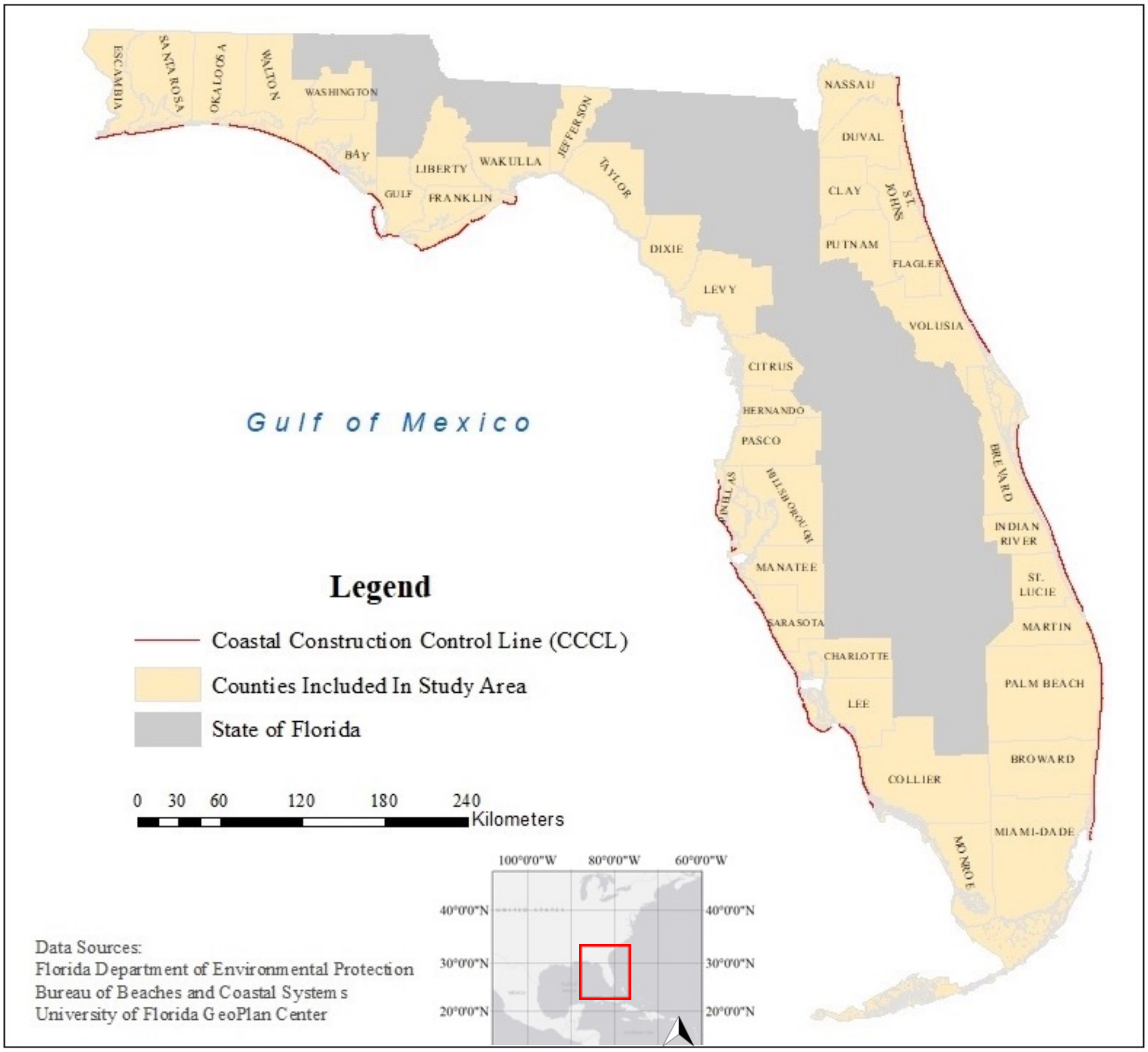
Study Area

This study is conducted in the state of Florida (latitudes from 24°52′ N to 31°02′ N and longitudes from 80°03′ W to 87°64′ W), which covers approximately 150,000 km^2 (United States Census Bureau). Florida is in the Southeastern U.S. where the *net precipitation* = $P > ET$ (where P is precipitation and ET is evapotranspiration) (Mitsch & Gosselink, 1993). Florida contains four terrestrial ecoregions: East Gulf Coastal Plain (NE), South Atlantic Coastal Plain (NW), Tropical Florida (S), and Florida Peninsula (central) (Olson et al., 2001). Florida is divided into two climatic zones: the warm temperate region (humid subtropical climate in central and N Florida) and the tropical region (consisting of tropical monsoon, savanna, and rainforest climate in S Florida) (Kottek et al., 2006). Over the last two decades, the annual temperature average was 21.9°C and precipitation was 1,350 mm (National Centers for Environmental Information, 2018).

The parent material/geology in Florida is comprised of medium fine sand and silt (27%), clayey sand (27%), shelly sand and clay (16%), limestone/dolomite (15%), peat (10%), sandy clay and clay (2.5%), and gravel and coarse sand (2.5%) (Florida Department of Environmental Protection, 2000). Dominant soil orders in Florida are Spodosols (32%), Entisols (22%), Ultisols (19%), Alfisols (13%), Histosols (11%), Mollisols and Inceptisols (3% together) (Vasques et al., 2010).

Florida's population increased 14.2% between 2010-2019 to a nearly estimated 21.5 million people (United States Census Bureau). Over three quarters of Florida's population lives in coastal counties and generate 79% of the state's economy (Kildow, 2008). While data was gathered to cover the entire state of Florida, the resulting study area was confined to a total of 39 counties in Florida (~105,827 km^2) (35 coastal counties plus 4 non-coastal counties based on available SLR data from NOAA) and includes roughly 1,350 miles of coastline (Kildow, 2008).

Figure 2. Map of Study Area



Materials

The Florida Land Use Cover, Forms, and Classification System (FLUCCS) Level I Land Uses attribute was used because it is extremely general in nature and divided into 8 classes (wetlands;

upland forest; urban and built-up; water; agriculture; transportation, communication, and utilities; and barren land) (Florida Department of Transportation, 1999). NOAA's SLR data was appropriate for the study area because Florida SLR is considered comparable to global SLR along the State's coastal areas (Merrifield et al., 2009).

The list of all 28 data sources used in this project is compiled in Figure 3 below and is continued on the next page.

Figure 3. Table of GIS Data Sources

	Data Source	Data owner/creator	Available from	Attributes/variables	Time data were collected
1	Florida Department of Environmental Protection (FDEP) Geospatial Open Data Portal	Florida Department of Environmental Protection (FDEP), Northwest Florida Water Management District (NFWMD), Suwannee River Water Management District (SRWMD), St. Johns River Water Management District (SJRWMD), Southwest Florida Water Management District (SWFWMD), and South Florida Water Management District (SFWMD)	https://geodata.dep.state.fl.us/datasets/statewide-land-use-land-cover	Statewide land use (polygon shapefile) attributes used were the Florida Land Use, Cover, and Forms Classification System (FLUCCS) Level I Land Use Codes	9/22/21
2	National Oceanic and Atmospheric Administration (NOAA)	Office for Coastal Management, National Oceanic and Atmospheric Administration (NOAA)	https://coast.noaa.gov/slrdata/	Sea level rise variables/attributes used were the water levels (1 ft and 8 ft under high tide) and areas	2020
3	FDEP Open Data Portal	Florida Department of Environmental Protection (FDEP), Bureau of Beaches and Coastal Systems	https://fdep.maps.arcgis.com/home/item.html?id=4674ee6d93894168933e99aa2f14b923	Coastal Construction Control Line (CCCL) (line shapefile) used to analyze where it intersects with rising sea levels	01/18/19
4	FGDL Metadata Explorer	University of Florida GeoPlan Center	https://fgdl.org/ File Name: COUNTYSHORE_AREAS_SEP15	Florida County boundaries with detailed shoreline and County names (polygon shapefile) used for illustrative purposes	07/07/05
5	FGDL Metadata Explorer	University of Florida GeoPlan Center	https://fgdl.org/ File Name: CENSTATE	State of Florida (polygon shapefile) used for for illustrative purposes	1990, 2000, 2006-2010, 2008-2012
6	FDEP Open Data Portal	Florida Department of Environmental Protection (FDEP), Bureau of Beaches and Coastal Systems	https://geodata.dep.state.fl.us/datasets/FDEP::coastal-construction-control-line-cccl-permits/about	CCCL permits shapefile used to analyze clusters	9/17/21
7	FGDL Metadata Explorer	University of Florida GeoPlan Center; Florida Department of Environmental Protection	https://fgdl.org/ File Name: WAFR_JAN21	Wastewater Facilities - January 2021*	2/26/21
8	FGDL Metadata Explorer	U.S. Environmental Protection Agency	https://fgdl.org/ File Name: EPARCRA_JUL20	US EPA Resource Conservation and Recovery Act (RCRA) Regulated Facilities in Florida - July 2020*	2/22/21
9	FGDL Metadata Explorer	Florida Department of Environmental Protection (FDEP)	https://fgdl.org/ File Name: SLDWST_JAN21	Solid Waste Facilities*	2/26/21
10	FGDL Metadata Explorer	Bureau of Archaeological Research	https://fgdl.org/ File Name: SHPO_STRUCTURES_JAN21	Historical Structure Locations in Florida - January 2021*	3/2/21

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	Data Source	Data owner/creator	Available from	Attributes/variables	Time data were collected
11	FGDL Metadata Explorer	Florida Department of Health	https://fgdl.org/ File Name: PUBLIC_POOLS_MAR18	Public Pools in Florida - March 2018*	7/19/18
12	FGDL Metadata Explorer	Florida Fish and Wildlife Conservation Commission - Fish and Wildlife Research Institute	https://fgdl.org/ File Name: MARINAS_JAN17	Marinas in Florida - January 2017*	11/15/17
13	FGDL Metadata Explorer	Florida Fish and Wildlife Conservation Commission - Fish and Wildlife Research Institute	https://fgdl.org/ File Name: MARFAC	Florida Marine Facilities*	6/28/06
14	FGDL Metadata Explorer	Florida Department of Environmental Protection (FDEP)	https://fgdl.org/ File Name: LQGS_JAN21	Large Quantity Generators of Hazardous Waste - January 2021*	2/26/21
15	FGDL Metadata Explorer	University of Florida GeoPlan Center	https://fgdl.org/ File Name: GC_SCHOOLS_MAR21	School Facilities (Public and Post-Secondary) in Florida - 2021*	7/3/21
16	FGDL Metadata Explorer	University of Florida GeoPlan Center	https://fgdl.org/ File Name: GC_LAWENFORCE_NOV18	Law Enforcement Facilities in Florida - 2018*	2018
17	FGDL Metadata Explorer	University of Florida GeoPlan Center	https://fgdl.org/ File Name: GC_HOTELS_AUG16	Hotels (Lodging Facilities in Florida - 2016)*	2016
18	FGDL Metadata Explorer	University of Florida GeoPlan Center	https://fgdl.org/ File Name: GC_HEALTH_AUG14	Health Care Facilities - 2014*	4/2/16
19	FGDL Metadata Explorer	University of Florida GeoPlan Center	https://fgdl.org/ File Name: GC_GOVBUILD_FEB13	Federal, State, and Local Government Buildings*	2/18/13
20	FGDL Metadata Explorer	University of Florida GeoPlan Center	https://fgdl.org/ File Name: EPASUPERFUND_JUL20	Registered Daycare Facilities in Florida - 2016*	10/15/17
21	FGDL Metadata Explorer	U.S. Environmental Protection Agency	https://fgdl.org/ File Name: EPASUPERFUND_JUL20	US EPA Regulated Superfund Sites in Florida - July 2020*	2/22/21
22	FGDL Metadata Explorer	Florida Department of Environmental Protection (FDEP)	https://fgdl.org/ File Name: CHAZ_JAN21	Hazardous Waste Facilities - January 2021 *	3/2/21
23	FGDL Metadata Explorer	Federal Communications Commission	https://fgdl.org/ File Name: CELLUR_AUG19	Registered Cellular Antenna Structure Locations - August 2019*	10/21/19
24	FGDL Metadata Explorer	U.S. Department of Transportation, Bureau of Transportation Statistics	https://fgdl.org/ File Name: BTS_BRIDGE_JUN18	National Bridge Inventory in Florida - June 2018*	7/29/19
25	FGDL Metadata Explorer	University of Florida GeoPlan Center	https://fgdl.org/ File Name: GC_CEMETERY_MAY19	Cemetery Facilities in Florida - 2019*	7/3/19
25	FGDL Metadata Explorer	Florida Department of Environmental Protection (FDEP)	https://fgdl.org/ File Name: BROWNFIELDS_AREAS_JUL19	Brownfields*	9/2/19
26	FGDL Metadata Explorer	Florida Department of Revenue	https://fgdl.org/ File Name: PAR_RELIGION_10	Religious Facility Parcels in Florida - 2010*	12/20/10
27	FGDL Metadata Explorer	University of Florida GeoPlan Center	https://fgdl.org/ File Name: AMINDIANLANDS_NOV17	American Indian Lands and Native Entities in Florida - 2017*	11/3/17
28	FGDL Metadata Explorer	Florida Fish and Wildlife Conservation Commission - Fish and Wildlife Research Institute	https://fgdl.org/ File Name: BOAT_RAMPS_MAR20	Boat Ramps in Florida - March 2020*	2/22/21

*Essential services

Methods

GIS data analysis was performed using several tools in Esri ArcMap and ArcGIS Online and was exported to MS Excel, as shown in Figure 4(a-d).

Figure 4.a. ***Data retrieval workflow:*** Data was collected and merged in ESRI ArcGIS. SLR data was compiled from all of NOAA's available Florida geodatabases and merged into two shapefiles for two different predictions: 1. Low (~0.3 m or 1 ft) and 2. Extreme (~2.4 m or 8 ft) SLR scenarios.

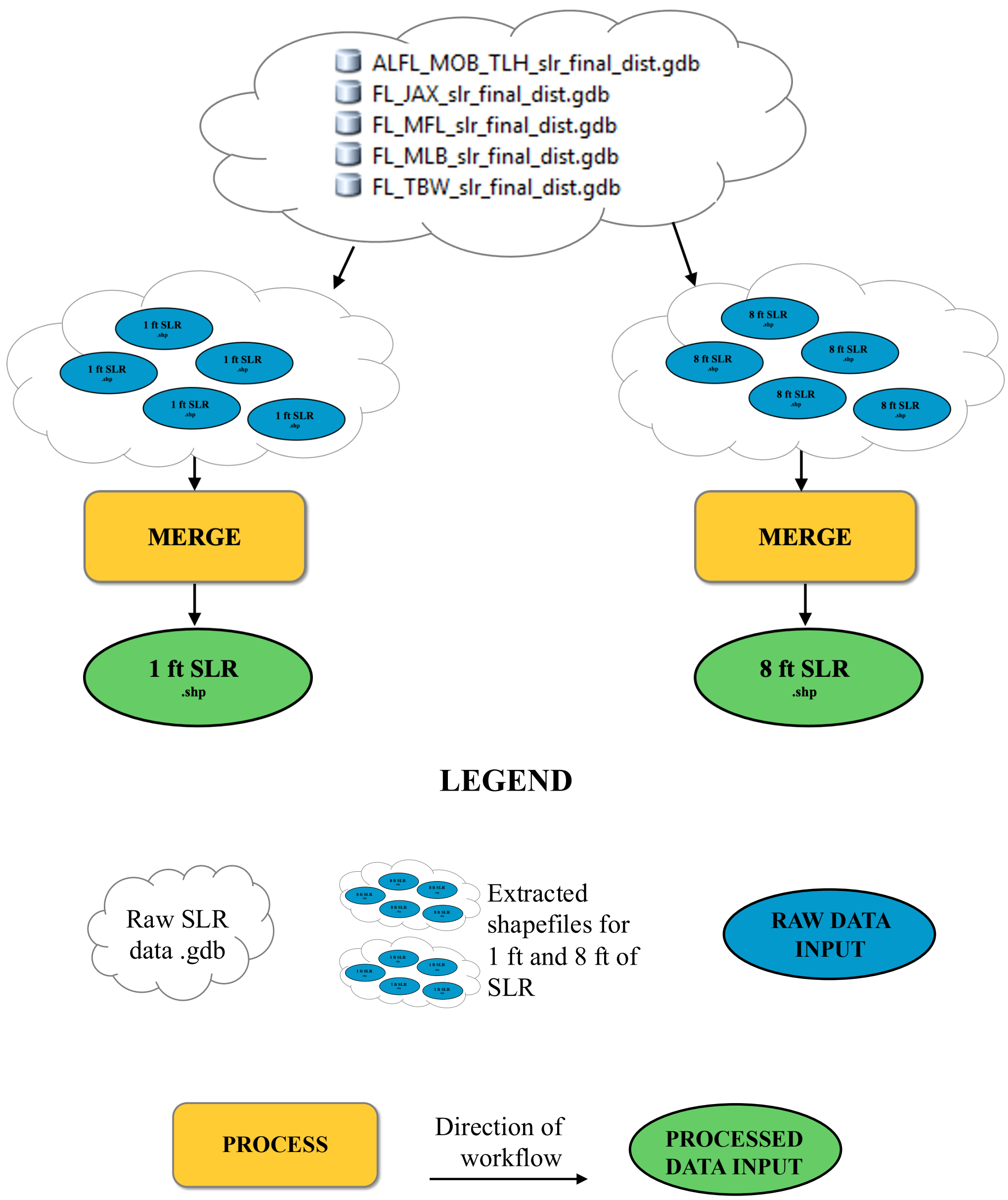
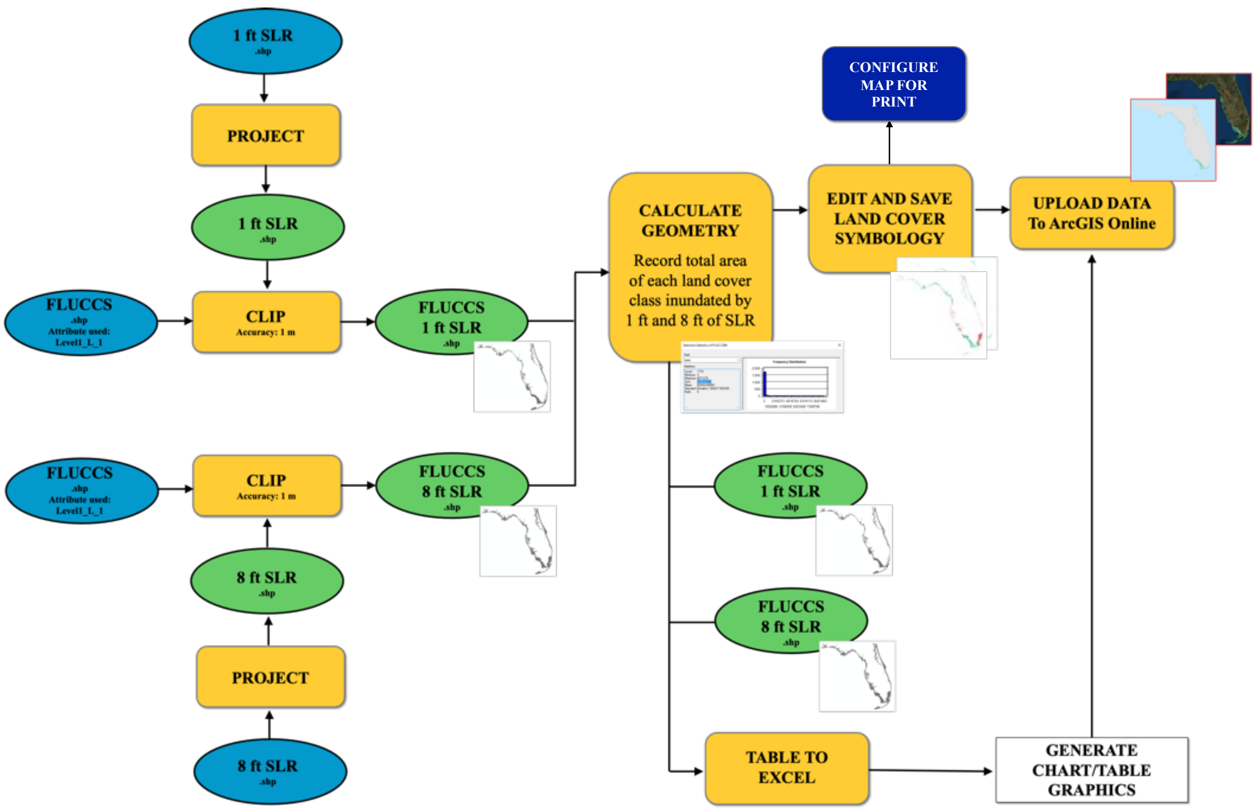
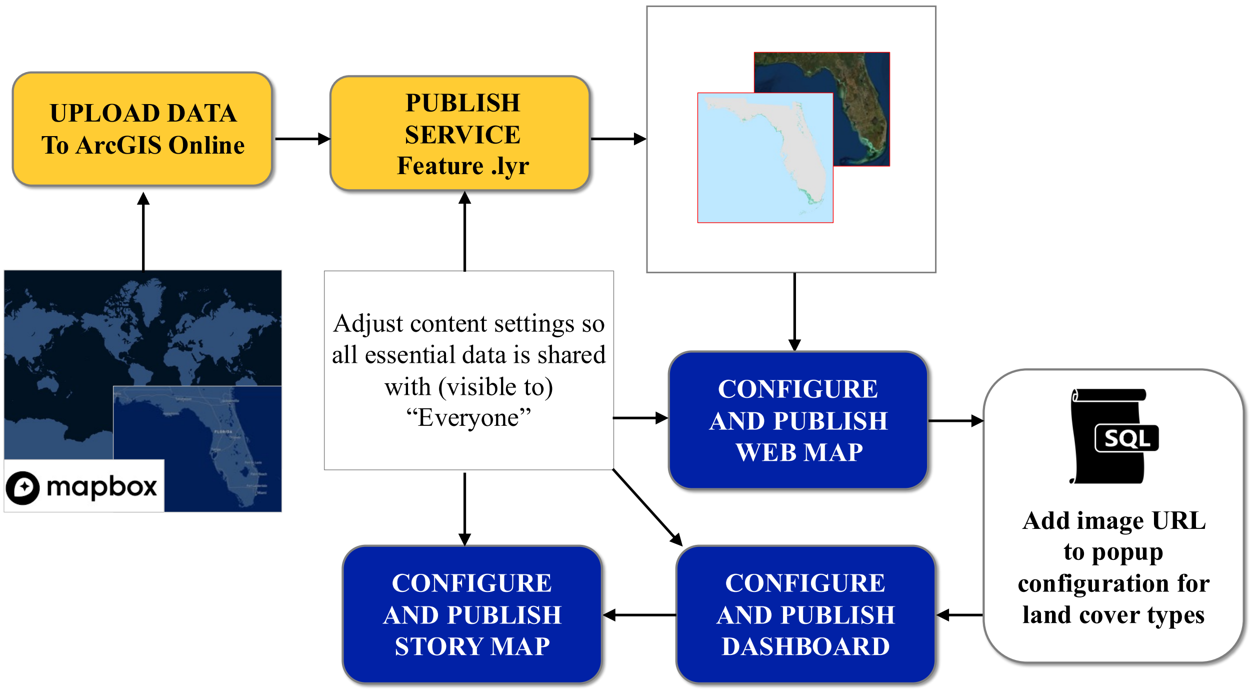


Figure 4.b. ***Data analysis workflow:*** SLR shapefiles were projected from GCS_North_American_1983 into the Albers Conical Equal Area projection and clipped with FLUCCS Level I Land Use. A new field was added to the attribute table, the calculate geometry tool was performed (area in km^2), and FLUCCS Level I Land Uses were filtered to then calculate statistics of the sum for the total area of each land cover classification. The attribute table was exported to MS Excel for additional evaluation.



Although not shown in the workflow above, the same process was repeated with essential services shapefiles (refer to Figure 3 for the table of essential service data sources used from FGDL) and the CCCL line shapefile that were batch clipped with the 1 ft and 8 ft SLR shapefiles. All GIS data was required to be reprojected to WGS 1984 before it was published as a service (feature layer) and uploaded to ArcGIS Online. Then, SQL was used to configure image URLs in the web map popups, and a custom basemap was created using Mapbox, as shown in Figure 4.c.

Figure 4.c. ***Workflow:*** Configuring and publishing map apps in ArcGIS Online to be shared with (visible to) everyone.



Finally, a calculate density analysis was performed on the CCCL permits in ArcGIS Online. The Kernel Density tool finds concentrations of CCCL permit clusters (O'Sullivan & Unwin, 2010) by calculating the density of CCCL permit point features around each output raster cell at a new (x,y) location using the formula shown below (ArcGIS Online, 2021):

$$Density = \frac{1}{(radius)^2} \sum_{i=1}^{n} \left[\frac{3}{\pi} \cdot pop_i \left(1 - \left(\frac{dist_i}{radius} \right)^2 \right)^2 \right]$$

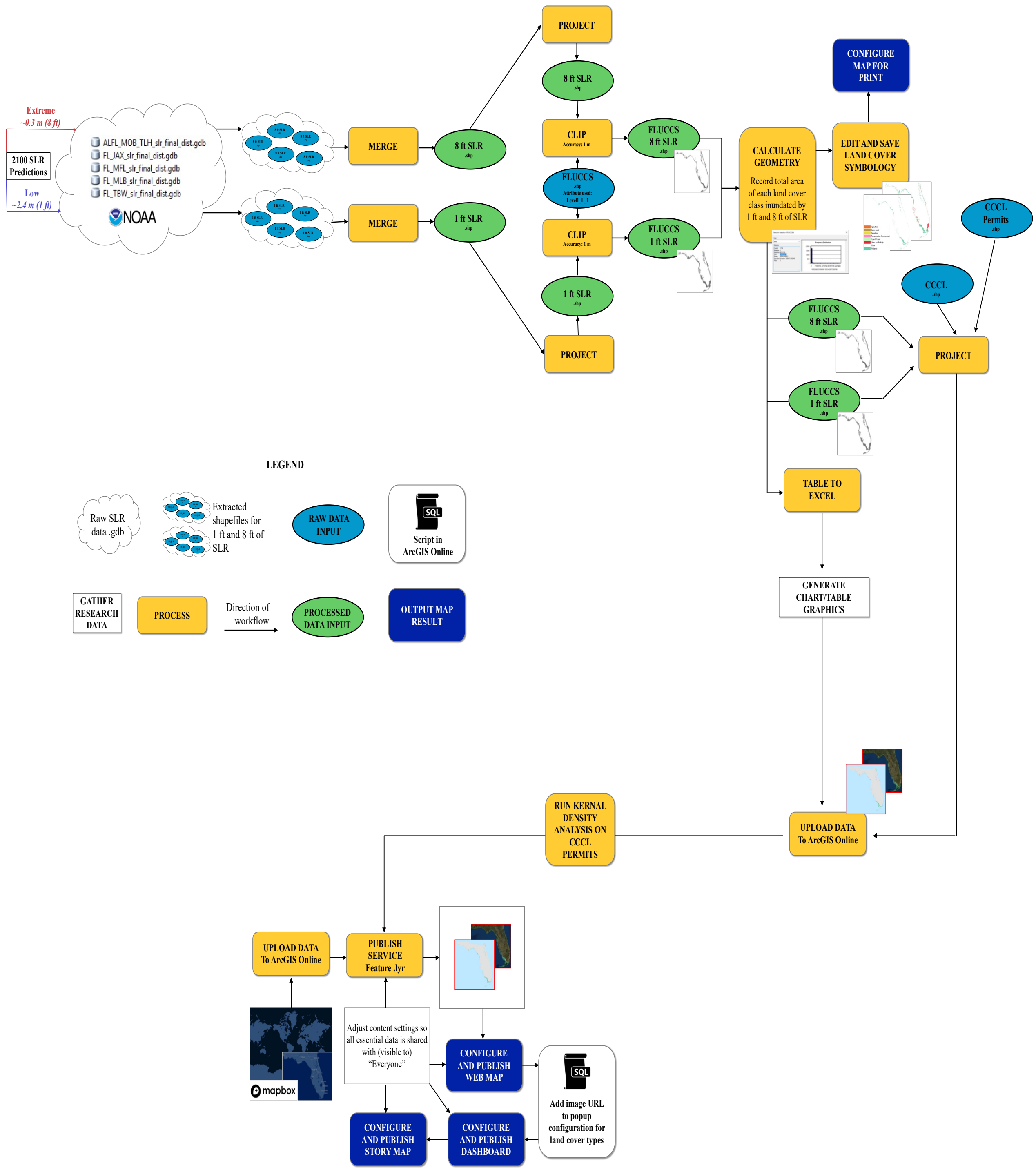
$$\text{For } dist_i < radius$$

Where: $i = 1,\ldots,n$ are input points; pop_i is population field value (number of points) of point i; $dist_i$ is distance between point i and (x,y) location.

Results were reclassified from Raster to Polygon before displayed in ArcGIS Online.

The overall workflow is shown in Figure 4.d.

Figure 4.d. ***Overall Workflow:*** Performed in Esri ArcGIS, ArcGIS Online, and MS Excel

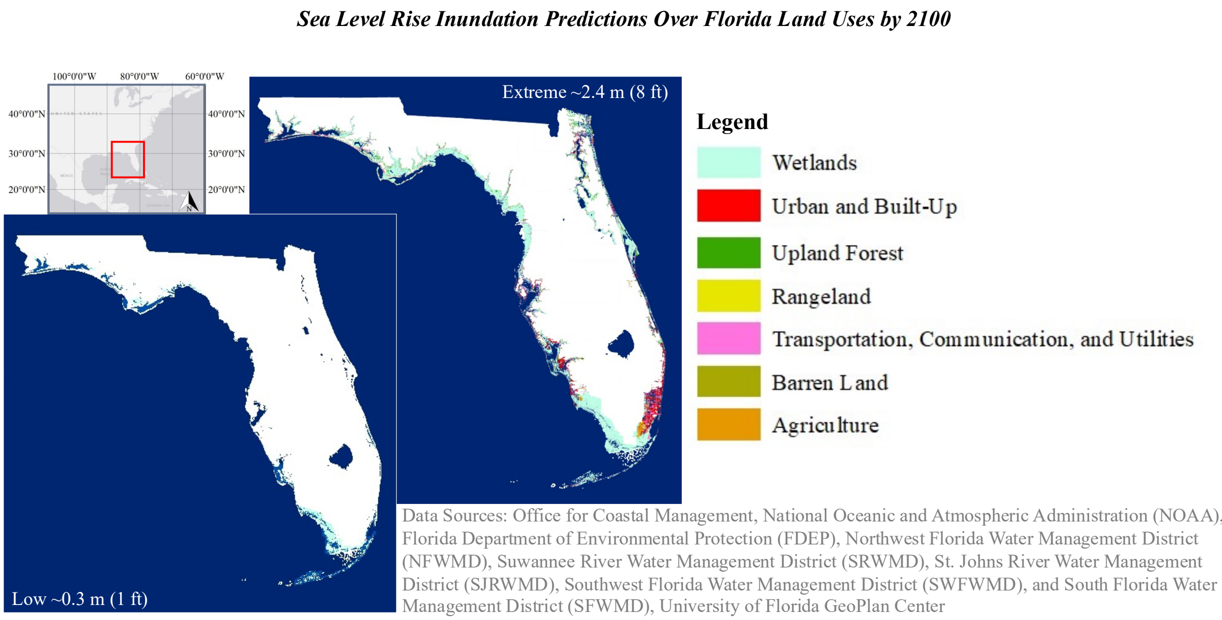


III. RESULTS

Land Use

The maps illustrate the estimated coverage of land uses that could be inundated under low and extreme SLR scenarios by 2100.

Figure 5. *Maps of low and extreme predictions of SLR over different land use types*



In addition, the estimated areal coverage of other land uses predicted to be inundated by SLR were compared in Figure 6(a-c).

Figure 6.a. *Table of estimated area of land use inundated by SLR in Florida based on low and extreme predictions by 2100*

SLR Scenarios by 2100	*Areal coverage (sq km) predictions of inundation under high tide by FLUCCS Level I Land Use*							Total Area (sq km)
	Wetlands	Urban and Built-Up	Upland Forest	Transportation, Communication and Utilities	Agriculture	Rangeland	Barren Land	
Low ~0.3 m. (1 ft)	4,327	68	33	30	2	8	15	4,482
Extreme ~2.4 m (8 ft)	8,622	2,956	1,261	252	383	279	107	13,859

The maps and calculations of total land area lost to SLR in Florida will overwhelmingly be wetlands, as shown in Figure 6(b-c).

Figure 6.b. Chart of total area (sq km) of land uses inundated by SLR in Florida

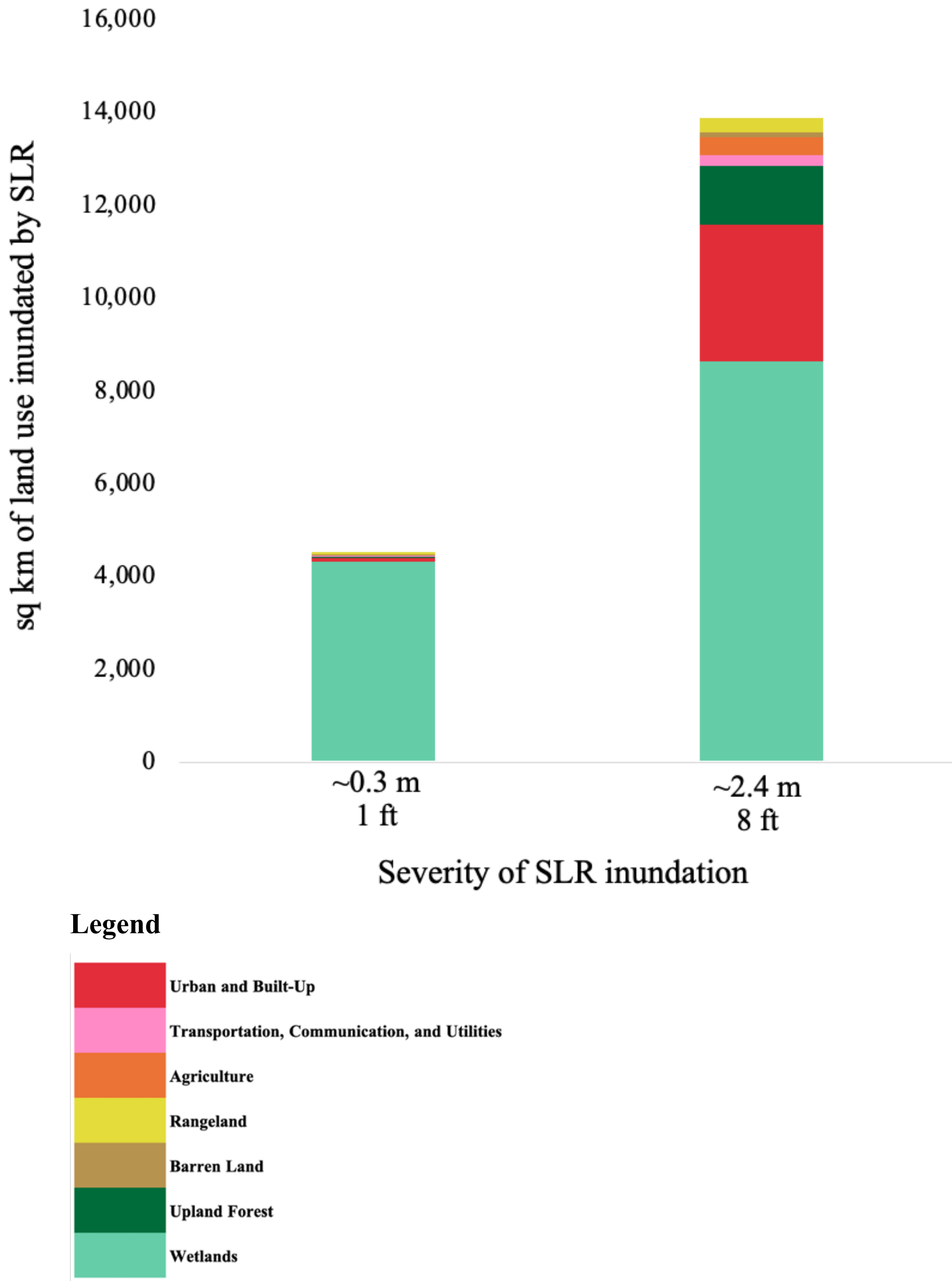
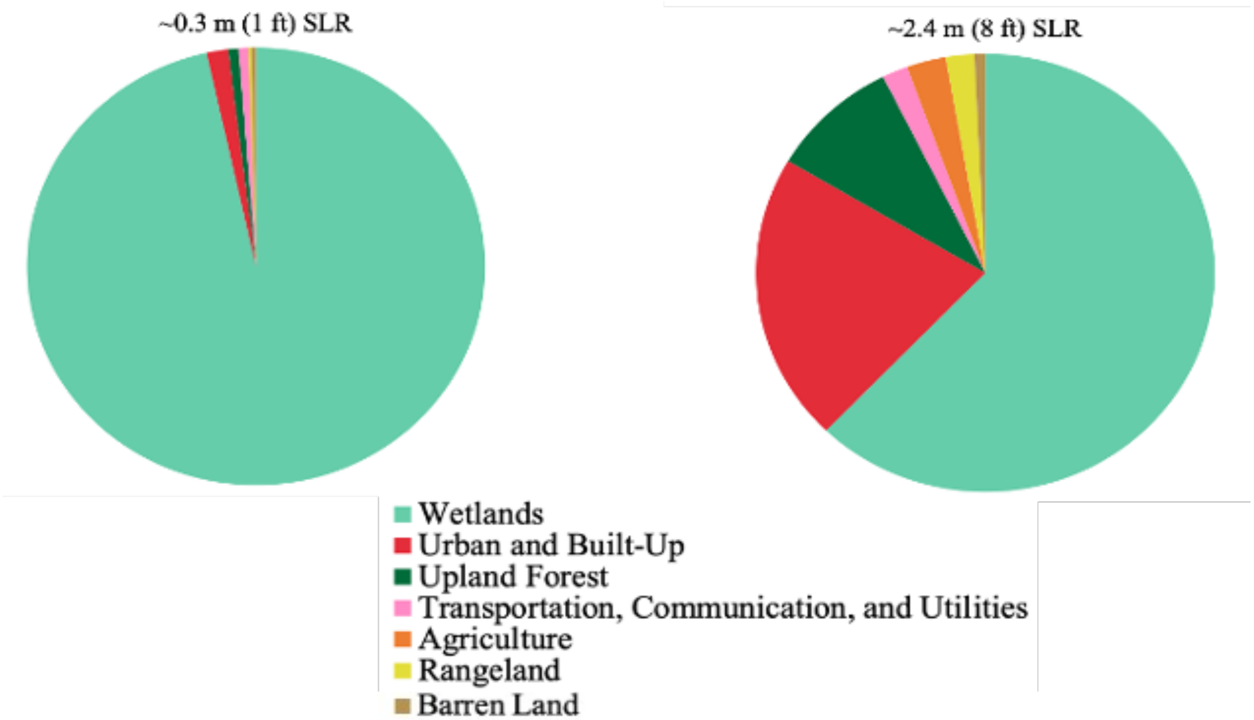


Figure 6.c. Visuals comparing total area (sq km) of land uses inundated by different levels of SLR in Florida by 2100



Essential Services

In addition to quantifying land covers, especially wetland loss, the results to compare the total number of other essential services that may be inudated under each SLR scenario are presented in Figure 7.

Figure 7. *Table of essential services inundated by SLR in Florida based on low and extreme predictions by 2100*

Type of Essential Service Data Sources: NOAA & FGDL.org	***Sea Level Rise Scenario*** ~0.3 m (1 ft)	~2.4 m (8 ft)
	Total quantity inundated under high tide	
Hospitals and Health Care Facilities	4	4,324
Fire Stations	1	376
Public schools and post-secondary institutions	-	778
Private Schools	20	837
Daycare Facilities	-	1,937

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Type of Essential Service Data Sources: NOAA & FGDL.org	***Sea Level Rise Scenario*** **~0.3 m (1 ft)**	**~2.4 m (8 ft)**
	Total quantity inundated under high tide	
Wastewater Facilities	1	392
Solid Waste Facilities	29	1,930
Large Generators of Hazardous Waste	-	108
US EPA Regulated Superfund Sites	-	108
Hazardous Waste Facilities	10	9,015
US EPA Resource Conservation and Recovery Act (RCRA) Regulated Facilities	10	10,611
Brownfields	7	177
Registered Cellular Antenna Structure Locations	-	163
Bridges	75	3,677
Government Buildings (Federal, State, and Local)	-	343
Law Enforcement Facilities	-	191
Historic Structures	50	38,734
Acres of American Indian Lands and Native Entities in Florida	~1*	~1,363***
Acres of Urban Areas	2,290	473,377
Public Pools	17	15,037
Marinas	46	2,445
Marine Facilities	40	2,164
Boat Ramps	15	1,025

*Miccosukkee Tribe of Indians land affected under 1 ft and 8 ft of SLR.

**Eastern Creek Tribe of Indians, Muscogee Tribe of Indians, and Seminole Tribe of Indians lands affected under 8 ft of SLR

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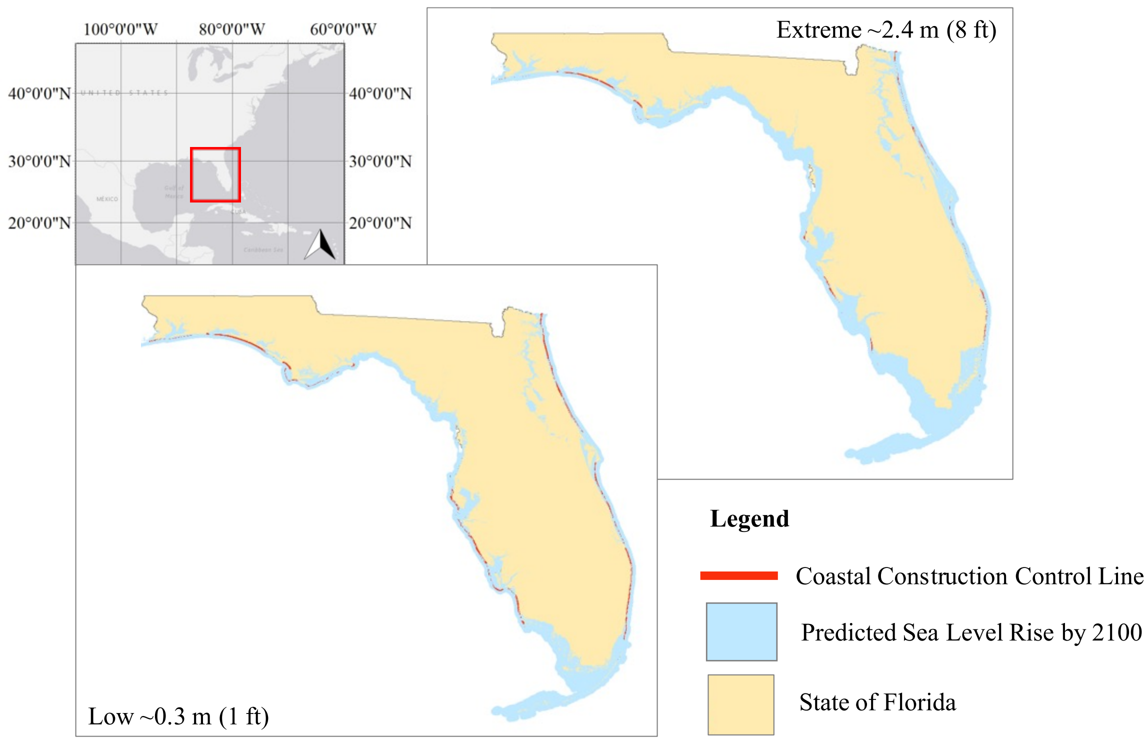
Type of Essential Service Data Sources: NOAA & FGDL.org	***Sea Level Rise Scenario*** **~0.3 m (1 ft)**	 **~2.4 m (8 ft)**
	Total quantity inundated under high tide	
Hotels	22	10,901
Golf Courses	12 courses and 38 acres	332 courses and 34,528 acres
Culture Centers	34	462
Cemeteries	3	390
Religious Facilities	10	2613
Civic Centers	4	184
Correctional Facilities	-	28
Rails	0.11 km	692 km
Airports	10	129
Powerlines	2.6 km	3157 km

CCCL

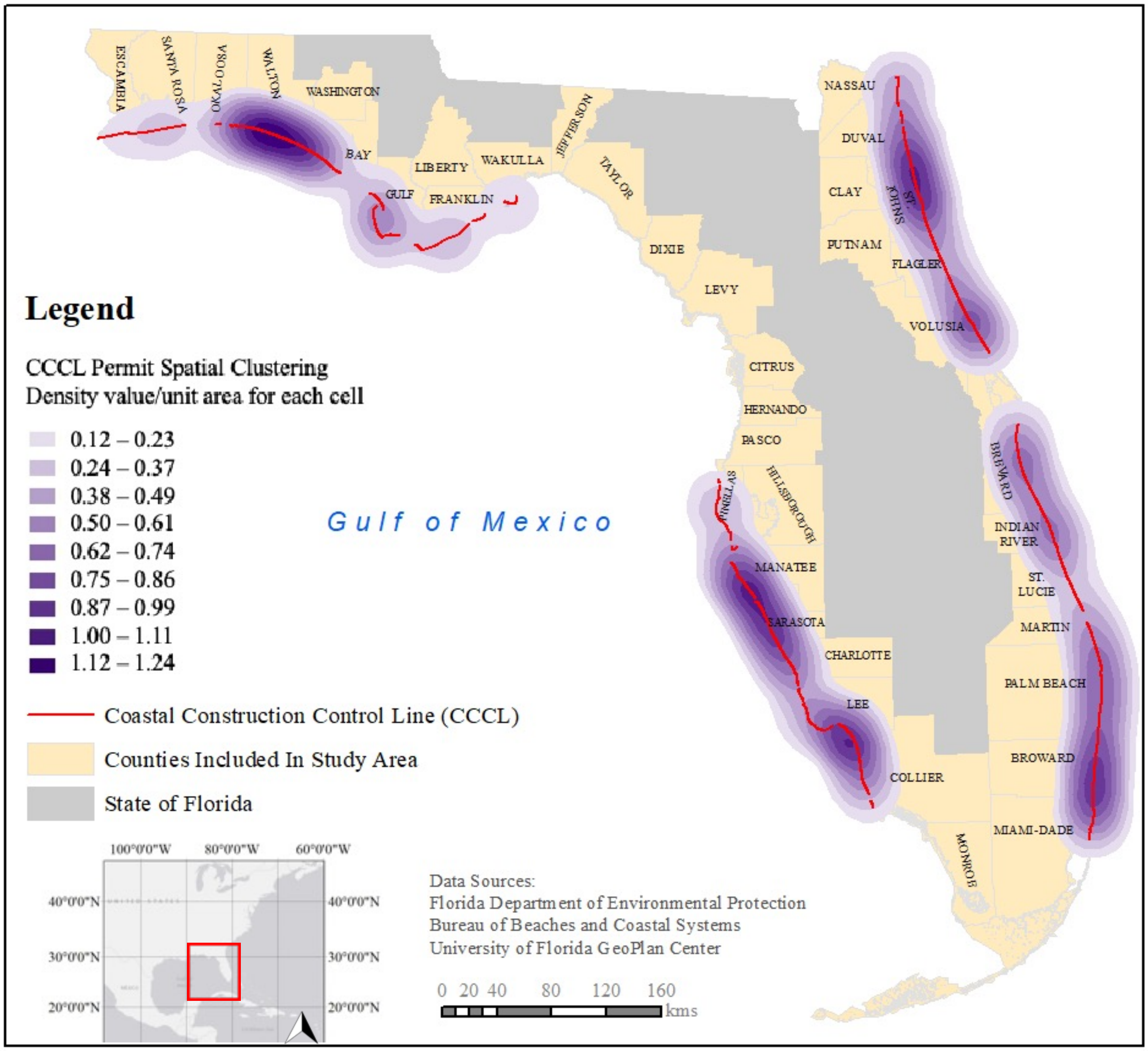
Results of the clipped CCCL to the low and extreme SLR predictions are shown in Figure 8, and output of the CCCL permit clusters is shown in Figure 9 on the next page.

Figure 8. Maps of Low and Extreme Predictions of SLR over the CCCL



Data Sources: Florida Department of Environmental Protection, Bureau of Beaches and Coastal Systems, University of Florida GeoPlan Center.

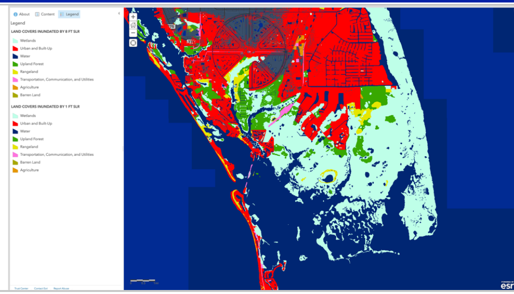
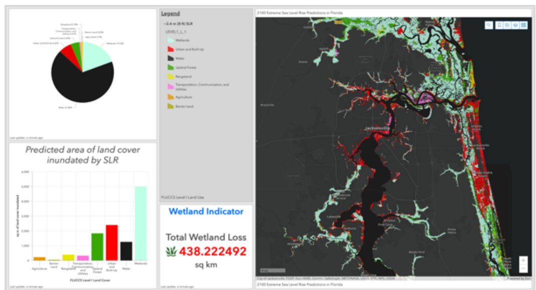
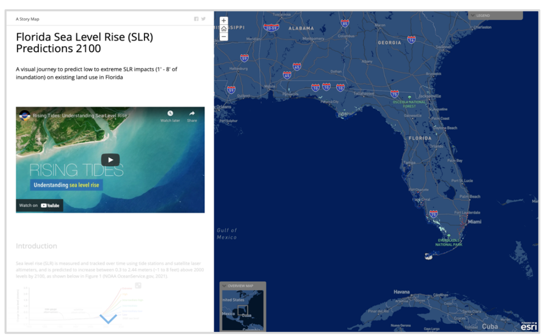
Figure 9. Map of CCCL permit clusters using Kernel Density in ArcGIS Online



ArcGIS Online

Finally, interactive data analysis is available for web users by following the links provided in Figure 10 on the next page.

Figure 10. Table of links to ArcGIS Online Results

ArcGIS Online App Type	Preview	URL
Web Map		https://arcg.is/e1iyH
Dashboard		https://www.arcgis.com/apps/dashboards/a8328a48b6984f638e50e5c6aade84ac
Story Map		https://ufl.maps.arcgis.com/apps/MapJournal/index.html?appid=a108a6c8ef9a4bf3a2602ea2a0f84caa

IV. DISCUSSION

The results of this study revealed that from low to extreme SLR scenarios, between 4,482 sq km to 13,859 sq km of land in Florida, could be inundated under high tide by 2100. While this study used different input predictions of SLR, it is comparable to the results of the Florida Oceans and Coastal Council (2010) that predicted 12,172 sq km (4,700 sq mi) of land could be inundated with 1 m of SLR by 2100. Like many other studies, these results demonstrate a wide range of SLR uncertainties based on the various unknown outcomes in when tipping points or planetary boundaries may be crossed (Rockström et al., 2009), and how humans may respond to curbing greenhouse gas emissions (Park et al., 1991). There is clearly a high degree of ambiguity in predicting the future of SLR, which is largely due to the complexity of earth's systems.

Land Use

The maps also clearly reveal where potentially inundated urban and built-up areas are located along the coast and whether they are (or are not) protected by a barrier of wetlands as the sea levels rise. This illustrates the importance of wetlands acting as a physical barrier to SLR inundation (Mitsch & Gosselink, 1993). The greatest total area of inundation will occur over wetlands, and then urban areas for both the low and extreme scenarios. However, far more urban areas will be inundated under the extreme scenario especially in the SE part of the state (Miami to Fort Lauderdale) and stretches of the Gulf Coast (Tampa to Naples). Much of the impacts to essential services and urban areas will occur where most people reside and visit – near the coasts.

The combination of SLR and higher water tables will lead to higher hydrostatic pressure of foundations and ground floor slabs, making infrastructure more vulnerable to structural damage, and even more so during times of coastal flooding and hurricanes (U.S. Global Change Research Program, 2009). Of notable importance impacted by this will be the total 68 sq km to 2,956 sq km of urban and built-up areas, and 30 sq km to 252 sq km of transportation, communication, and utilities (especially those that do not have wetlands as barriers) that are most vulnerable to becoming inundated under low to extreme SLR predictions, respectively. Additionally, up to 1,937 daycare facilities, up to 778 public schools and post-secondary institutions, and between 20 to 837 private schools are predicted to be inundated by SLR by 2100. These populated areas and essential services alike may be considered priority areas with the greatest needs to effectively plan for SLR.

In addition to losses of urban areas and essential services, between 33 sq km to 1,261 sq km of upland forest may be inundated by 2100, and these ecosystem responses to SLR and saltwater inundation deserve extra attention for future studies (Saha et al., 2011). Also, between 15 sq km and 107 sq km of barren land may be affected by low to extreme scenarios of SLR inundation, and these areas should be assessed for their suitability to be converted to restoration areas or place higher standards for future development that fully accounts for the risks of SLR and more extreme weather events.

While the urban areas and essential services are critical to protecting human wellbeing, it is important to note that wetlands provide their own unique ecosystem services that make up the largest total area of land cover that could be lost to SLR under both low and extreme scenarios. Depending on the level of protection afforded, the SLAMM (Sea Level Affecting Marshes Model) estimated 26 to 82 percent of U.S. coastal wetlands could be lost with 1 m of SLR (Park et al., 1991; Lee et al., 1991). Lee et al. (1991) predicted the northeastern Florida coastline would lose 40 percent of wetlands with a 1 m SLR. However, mangrove abundance has been studied extensively, was closely related to fewer freeze events in northeastern Florida (Cavanaugh et al., 2014), and it is predicted to expand northward along the east coast of the US over the next half century (Cavanaugh et al., 2015). With mangrove composition shifting and expanding, its future trend along with coastal wetlands remains uncertain because mangroves need to withstand many challenges in the Anthropocene such as SLR, atmospheric warming, and land use change (USDA, 2021).

Threats to wetlands are widely documented in scientific literature. Coastal wetlands could be lost if SLR is amplified by more extreme weather events (Klemas, 2011). Altered hydroperiods caused by human development, drainage to accommodate development, and polluted upstream stormwater runoff are some of the other major threats to wetlands (Mitsch & Gosselink, 1993). A change in SLR or sedimentation rate of as small as 1-2 millimeter/year can impact whether a marsh expands, retreats, or degrades (Mitsch & Gosselink, 1993). Tidal wetlands could disappear completely if the rate of SLR surpasses their capacity to accumulate sediment (Florida Oceans and Coastal Council, 2010).

The importance of protecting wetlands cannot be understated as they play a critical role in regional water-flow patterns that intercept stormwater runoff and discharge (Mitsch & Gosselink, 1993). Peak flows produce the worst flooding damage, but wetlands serve to physically reduce the danger of flooding (Mitsch & Gosselink, 1993). Additional wetland benefits include accumulating and storing organic matter (peat accumulation); reducing erosion; maintaining drinking water quality, surface and ground water levels, and waterflows; filtering nutrients and chemicals; providing food, fiber, and fodder for humans and animals; and acting as a storehouse for genetic material that provide bird watching, fishing, boating, and other recreational activities; as well as scientific inquiry opportunities, psychological support, aesthetics, and spiritual values for human beings where replacement is not feasible (Folke, 1991).

While there are many uncertainties to predicting the future of human activities and SLR, what is known is that wetlands and soil can play a key role in climate change abatement by reducing greenhouse gases and acting as a carbon pool (McBratney et al., 2014; Mitsch & Gosselink, 1993). Soils can either be a source or sink for atmospheric CO_2 depending on the land use and soil management (Lal, 2001). After fossil fuels, soil C emissions make up the second largest source of C emission into the atmosphere (Lal, 2001). Soil organic C is lost to the atmosphere when soil is cultivated or converted from natural to agricultural systems (Lal, 2001). These human activities lead to accelerated decomposition of soil organic matter and enhanced greenhouse gas emissions of CO_2, CH_4, and N_2O from the soil to the atmosphere (Lal, 2001). Development and adoption of appropriate soil management technology is key to realizing soil C sequestration potential (Lal, 2001).

Addressing soil quality provides society with an opportunity to mitigate global warming and SLR through C sequestration. Society not only relies on soil security for climate change abatement, but also the actual foundation for our physical and cultural environment, source of raw materials, and food security (McBratney et al., 2014). Nearly all (>95 percent) of food consumed by humans is grown using soil as the medium (Food and Agriculture Organization of the United Nations, 2015), and it is predicted that between 2 sq km to 383 sq km of agricultural lands and 8 sq km to 279 sq km of rangeland could be inundated by low and extreme scenarios of SLR in Florida by 2100. Loss of this productive agricultural and rangeland would put stress on Florida's food system and impact the communities who rely on using soil as the foundation of their livelihoods.

Essential Services

In addition, the impacts of SLR in Florida extend beyond the state's boundaries. Protecting Florida's ports is essential as they facilitate globalization and are a gateway for U.S. exports to 22 foreign countries located within 2000 miles (Kildow, 2008). Between 40 to 2,164 marine facilities, 0.11 km to 692 km of rail, and 10 to 129 Florida airports may be at risk of SLR under low to extreme scenarios by 2100.

Florida is one of the top tourist destinations in the U.S. and worldwide (Harrington et al., 2017). In addition to many of the transportation services needed to travel to and from Florida, a vast range of recreational sites that attract much of the tourism and economic development in Florida could be inundated under either low or extreme SLR predictions. These include 46 to 2,445 marinas, 15 to 1,025 boat ramps, 17 to 15,037 public pools, 22 to 10,901 hotels, 12 golf courses (38 acres) to

332 golf courses (34,528 acres), 10 to 129 airports, and 34 to 376 cultural centers. With tourism being one of the largest economic industries in Florida, SLR, hurricanes and more extreme weather events have potential to impact the future prosperity of Florida's tourism sector by negatively impacting travel decisions of tourists (Harrington et al., 2017).

It is also crucial for the safety and wellbeing of the public that hospitals and health care facilities remain adequately prepared for SLR and extreme weather events. In Florida, between 4 to 4,324 hospitals and health care facilities could be at risk of SLR inundation by 2100. Further, climate change and SLR threaten human health and lives especially in areas where economic conditions prevent construction of mitigation or other sea defense structures (Haines et al., 2006). While SLR can cause direct danger of displaced populations or risk of drowning by storm surge, regional and local weather changes can also lead to indirect adverse health effects, such as heat-related illnesses and deaths, air pollution, infectious diseases, and malnutrition (Haines et al., 2006).

Additionally, several government facilities and other essential services that society relies on for protecting human health, life, and property could be inundated by SLR. These include up to 343 government buildings (Federal, State, and Local), 1 to 376 fire stations, 29 to 1,930 solid waste facilities, 1 to 392 wastewater facilities, up to 191 law enforcement facilities, up to 28 correctional facilities, up to 163 registered cellular antenna structures, 2.6 km to 2,157 km of powerlines, and 4 to 184 civic centers. While buildings may be rebuilt in certain areas or retreated inland, many central facilities (e.g. water treatment plants) will be unable to be relocated due to their location that is limited by the service areas they support (Deyle et al., 2007). Municipal sewer systems will need to be strengthened to reduce groundwater seepage, as well as water and wastewater treatment plants at low elevations that will require additional flood protection (Bloetscher et al., 2009). Further, there is a need to evaluate the ability of existing engineering solutions (e.g. dunes, dikes, seawalls, sea gates, locks, pumping stations) to withstand the pressures from SLR and likelihood of more intense hurricanes and extreme rainstorms (Heimlich et al., 2009).

Several environmental hazards were identified as being vulnerable to low and extreme SLR scenarios, which include up to 108 US EPA Regulated Superfund Sites, up to 108 large generators of hazardous waste, 10 to 9,015 hazardous waste facilities, 10 to 10,611 US EPA Resource Conservation and Recovery Act (RCRA) Regulated facilities, and 7 to 177 brownfields. SLR is dangerous to populations that live near hazardous environmental areas, such as brownfield redevelopment sites, because floodwaters can spread harmful contaminants that endanger human health, animals, and the environment (EPA, 2020).

Also, a wide variety of historical and cultural sites could be inundated by SLR by 2100. These include between 1 ac to 1,363 ac of American Indian lands and Native entities in Florida which would directly impact the Miccosukkee Tribe of Indians lands first under a low scenario of SLR, as well as lands of the Eastern Creek Tribe of Indians, Muscogee Tribe of Indians, and Seminole Tribe of Indians under an extreme SLR scenario. Additionally, 50 to 38,734 historical structures, 10 to 2,613 religious facilities, and 3 to 390 cemeteries fall within the lands that could be inundated under low to extreme SLR predictions. Among the valuable artifacts that we could lose to SLR is knowledge of humanity's history (Yale, 2017), especially pertaining to how ancient Floridians adapted to SLR in the past.

CCCL

Maps that show where the CCCL could be inundated may be used by today's planners to help strategize for SLR. Mitigation and adaptation are two of the possible responses to SLR (Nicholls, 2011). Adaptation involves planned retreat (moving coastal development inland), accommodation (adjusting human use of coastal zones) and protection (renourishing beach and dune systems, seawalls) (Nicholls, 2011). As SLR occurs, the CCCL program and jurisdictional line should be reevaluated and adjusted based on the landward shift of the 100-year event erosion line from which its boundary is defined (Deyle et al., 2007). It is important that coastal management plans monitor responses to higher projections of global SLR, be flexible based on the latest credible scientific information and inclusive of environmental, economic, and social impacts (Williams, 2013).

Unsurprisingly, the most pronounced hotspot distribution of CCCL permits appear to be clustered in the most populated metropolitan areas of the Florida coastline. These results are comparable to the significant clusters of wetlands permits identified along the coastlines and southern areas of the state (Brody & Highfield, 2005). The clustered distribution of CCCL permits is worth further investigation, as it could provide important clues about the CCCL program's effectiveness at protecting the shorelines from erosion and SLR. For example, it would be interesting to investigate what impacts the CCCL program had on protecting coastal infrastructure and mitigating effects of local SLR where CCCL permit clusters were identified versus where no significant clusters have occurred. While there is clear evidence that wetlands should be protected for their various values to society, this paper suggests additional research should also focus on actions taken through the CCCL permitting program, as they may play a significant role in protecting Florida's coastal infrastructure especially with the threat of SLR in the Anthropocene.

Limitations

One of the limitations of this paper is that socioeconomic factors were not included in the study. However, incorporating this data would be useful in future studies to compare how different levels of SLR inundation estimates may affect property values and vulnerability, incomes, among other socioeconomic impacts.

It is worth noting that while SLR predictions have so far been met or exceeded, nobody knows with absolute certainty exactly when SLR or other tipping points could occur in the Anthropocene. Intergovernmental Panel on Climate Change (IPCC) projections were found to be underestimated by a scale of 3 in the first well-constrained continuous model for SLR that analyzed data from over the past 2000 years (Grinsted et al., 2009). There is ongoing debate among researchers around the specific magnitude, arrival, and time frame projections of SLR, with even higher levels of uncertainty and disagreement increasing towards the end of 21st century (Grinsted et al., 2009). The research debate is centered around the many unknowns to how humanity will react to changing coastlines and variations in storm/tidal inundation, how governments (local and national) choose to respond to adapt, and how mitigation may impact the global processes already contributing to SLR (McAlpine & Porter, 2018).

Also, while Florida SLR is expected to be similar to global SLR (Merrified et al., 2009), others point out that global SLR is not expected to have uniform consequences across the Earth because of variations in local or regional vertical crust movements (subsidence), resistance to erosion, different wave climates, and altering longshore currents (Gornitz, 1991). Input data had several limitations. For example, SLR data by NOAA does not account for erosion, subsistence, and future construction. Additionally, sea levels are shown as they would be under highest tide, so results will be different under low tide.

Further, time periods of GIS data collected for some essential services date back to 2006 and are expected to produce different results if the current numbers were used in this analysis. Also, the time periods for land covers were collected between 2012-2019 (last updated May 24, 2021) while the predictions for SLR are based on 2000 sea levels. This study would be improved with all input data collected from the same baseline year, especially because Florida's shoreline is not in a fixed or permanent state, as it is both retreating and advancing with sediment accumulation from hurricane landfalls and beach renourishment activities over time (Sallenger et al., 2006). Additionally, scientists are challenged with separating the effects of SLR from impacts caused by storm events and from inlet or beach management activities (Florida Oceans and Coastal Council, 2010).

Finally, this paper is missing Florida's inland habitats that are impacted by SLR in other ways besides direct inundation (e.g. groundwater intrusion and higher storm surge) (Langevin et al., 2005). Ecosystem services from coastal, marine, freshwater, and terrestrial ecosystems, are all impacted by a changing climate and their accelerated degradation is expected to increase over the future decades (WMO, 2021). The importance of understanding how these ecosystems will respond to SLR cannot be understated because their degradation is reducing their potential to support human well-being and is harming their capacity to build resilience (WMO, 2021).

Future Research Recommendations

There is a need for additional follow-up studies on SLR, including analysis of saltwater intrusion and groundwater table rise, as well as monitoring SLR impacts and effectiveness of adaptation approaches over time (EPA, 2020). Additionally, it is not water alone, but local subsidence ground movements also have a significant impact on SLR (NASA, 2021). Techniques to detect and measure subsidence, such as the networks of global navigation satellite system (GNSS) reflectometry, and improvements in computer processing capabilities are growing at an increasing pace, and should help improve the understanding of complex dynamic earth system processes affecting SLR (NASA, 2021).

The integration of satellite remote sensing data, ground-based data, and in situ and field observations lead to new advances in our understanding of complex Earth system processes (Tralli et al., 2005). Additional research using remote sensing imagery may provide a more suitable land cover classification for a specific baseline year that is being studied. Use of remote sensing imagery for more updated land cover classes (i.e. replace FLUCCS in the workflow with Landsat- or MODIS-derived land cover classification data) is another approach to identify short-term variations and long-term trends of hurricanes and SLR (Klemas, 2011). While multispectral imagery is practical for most SLR research applications, a combination of light detection and ranging (LiDAR) and hyperspectral imagery may improve our understanding of wetlands hydrological conditions, topography, and bathymetry (Klemas, 2011). However, the relatively short time spans of satellite datasets warrant longer periods of remote sensing observations to determine the interannual and decadal variations from long-term trends in SLR (Yang et al., 2013), and observations will become more robust as more data is collected over time. Deep learning (a machine learning method that uses contextual information in pattern recognition) also deserves more attention for improving hyperspectral and multispectral image land cover classifications (Padarian et al., 2019).

To protect coastal resources, it is important to understand the *rate* of SLR over time in addition to how much SLR occurs. An accelerated rate of SLR would have serious impacts on coastal wetlands distribution throughout the world (Park et al., 1991). The use of high temporal resolution in-situ digital repeat (phenocam) imagery measurements could help improve our understanding vegetation and water dynamics (color and depth) in intertidal mangrove habitats, which may play an important part of mitigating environmental changes in the Anthropocene (Songsom et al., 2021).

There are many opportunities for future SLR studies, as both commercial and non-commercial GIS software are proven to be feasible options that can be used to perform SLR and coastal management analysis (De Lima et al., 2021). De Lima et al. (2021) provides an overview of several GIS-based modeling approaches using open-source data with analyses that only take a few minutes to run, including the End Point Rate for QGIS, Uncertainty Bathtub Model, and Bruun Rule for Google Earth Engine. Additionally, the methods outlined in this paper may be replicated to compare other essential services or building regulations besides the CCCL using ArcGIS or similar software (e.g. ENVI, QGIS) with FLUCCS and SLR data that are accessible online. For example, additional analyses are recommended to study the vulnerability of where Florida Counties' Comprehensive Plans concentrate future development in areas prone to SLR, because Frazier et al.'s (2010) study of Sarasota County found that future population growth and development was concentrated in coastal future high hazard zones of SLR.

To better address SLR and other wicked environmental problems, it is also imperative to learn *how* to integrate the appropriate changes (rather than remaining focused only on *what* changes need to be made) (Hulme, 2010). An interdisciplinary research approach with collaboration among stakeholders from a diversity of backgrounds using a multidimensional perspective is needed to address physical, social, and health vulnerabilities associated with SLR (Bloestscher et al., 2016). The risks associated with SLR have already impacted real-estate values in Miami, putting strain on funding for location governments through local tax dollars needed to mitigate SLR (McApline & Porter, 2019). Climate gentrification is also occurring where populations are moving investments towards neighborhoods with higher elevations as they are deemed to be less at risk of flooding (McAlpine & Porter, 2018). Many stakeholders in Florida and around the globe will be affected by SLR, so it is crucial that individuals, communities, and governments all work together to address these issues with urgency taking reasonable measures to reduce the risk of tidal flooding (McAlpine & Porter, 2018).

V. CONCLUSION

In summary, all the major FLUCCS Level I land uses, essential services, and the CCCL analyzed in this study could face varying degrees of inundation by SLR. A total of 4,482 sq km to 13,859 sq km of land in Florida could be inundated under high tide by 2100 based on data sources provided by NOAA and FDEP, which is similar to results from the Florida Oceans and Coastal Council (2010). Additionally, maps reveal where various land uses and the CCCL could be inundated by low and extreme SLR scenarios, as well as where CCCL permit spatial clustering occurs in densely populated areas along the coast. One of the major outcomes that this study demonstrates is the importance of wetlands in protecting other land uses, especially urban and built-up areas, from inundation by SLR.

Additional studies are recommended to use the methods described here as a framework to perform ongoing analyses of SLR on various land uses using remote sensing imagery over time and other coastal regulations besides the CCCL. For example, it would be worthwhile to assess where future development is being concentrated in relation to SLR vulnerability. Research is also needed to study the effects of SLR on inland habitats, the rate of SLR over time, how governments and human migration patterns are directing development into (or away from) highly vulnerable SLR areas, as well as *how* to integrate changes needed to solve wicked environmental problems in the Anthropocene.

It is crucial that planning for SLR fully considers the long-term economic, social, and environmental costs and benefits of different strategies for adaptation (Williams, 2013). For example, the dollars spent on beach nourishment have been essential to sustain Florida's tourism industry that relies on revenue generated by visitors of the beaches and significantly impacts the overall national economy (Kildow, 2008). The importance of protecting wetlands as a barrier to

SLR and environmental changes cannot be understated to protect the future of Florida's coastal communities. While replacement technologies (e.g. redraining ditches and pipelines, saltwater filtering, water purification plants) are useful in assisting with wetland hydrologic functions, there is no replacement possible for the species diversity, recreational values, and spiritual values that wetlands have provided for generations (Mitsch & Gosselink, 1993). Although the specific timing details of projections for future SLR remain uncertain, what remains undisputed is that soil and water are essential for human life on earth. Therefore, the importance of using GIS to monitor and learn more about the complex earth system processes that contribute to SLR cannot be understated to protect the future of humanity in the Anthropocene.

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