Sea level rise submergence simulations suggest substantial deterioration of Indian River Lagoon ecosystem services by 2050, Florida, U.S.A.

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Abstract
The Indian River Lagoon is a 250-km long Estuary of National Significance located along the east central Florida coast of the USA. NOAA tidal records generated at a station located in the central reaches of the estuary indicate sea level rise has accelerated over the past 20 years to an average of 9.6 ± 1.6 mm yr^{-1} (2003–2022) and it is expected to continue accelerating over the duration of this century. This investigation simulated submergence of the estuary using the on-line geospatial tool Future Shorelines to evaluate the effects of sea level rise on a suite of natural and built attributes that either contribute to or degrade ecosystem services. The simulations are based upon the median NOAA high scenario-based sea level rise trajectory in target years 2050, 2070, and 2100. By 2050, 23% of the public motorized boat ramps and 83% of the spoil islands that provide recreation and conservation services will be inundated. Thirty-three percent of the known or likely septic systems in the study domain will be submerged by 2050. Sea level rise does not reach any of the eleven wastewater treatment plants considered in this study over the next 25 years. Seagrass distribution is expected to decline 32% by 2050 due to a reduction in substate area located above the light-dependent median depth limit. By 2100, all ramps, spoil islands, septic systems, and six wastewater treatment plants will be totally submerged. These findings are conservative because the submergence simulations do not consider (1) the presence of groundwater, (2) that septic systems and the conveyance pipework that deliver wastewater to the treatment facilities are below grade, or (3) stochastic events (e.g., hurricanes).

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Title Page

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Keywords: ecosystem services, Florida, Indian River Lagoon, sea level rise, submergence modeling

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Introduction

The Indian River Lagoon (IRL) was recognized by the Environmental Protection Agency (EPA) as an Estuary of National Significance in 1990 and it is one of 28 National Estuary Programs (NEP) established in the United States. Since then, a growing body of scientific evidence has emerged indicating the ecological integrity of the lagoon has degraded over historical times due to a decline in water quality (Adams et al., 2019; Sigua et al., 2000) that is attributed to watershed urbanization (e.g., stormwater runoff, septic systems). Two recent studies (Parkinson et al., 2021a, 2021b) conducted on behalf of the IRL NEP determined increasing impairment of water quality and ecosystem function is highly likely under conditions of future climate change and concomitant sea level rise (SLR). For example, rising sea level is expected to increase the flux of nutrient pollution into the estuary, degrading water quality and related ecosystem services that depend upon clean water.

Estuaries provide many critical ecosystem services (c.f., Barbier et al., 2011) and the risks to them posed by climate change and accelerating SLR extend well beyond the IRL. For example, nutrient pollution from stormwater, septic systems (on-site treatment and disposal systems; OSTDS), and wastewater treatment plants (WWTP) already present a substantial management challenge to many of the NEPs located throughout North America and accelerating SLR is expected to magnify those threats as they are gradually inundated (Parkinson, 2023). Hence, there have been a growing number of ecological risk assessments to evaluate ecosystem service vulnerability and provide a foundation from which to develop effective adaptation management plans (Alemu et al., 2024; Gilby et al., 2020; Kassakian et al., 2017; Williams et al., 2019). Most considered a single living resource (e.g., wetlands, seagrass, birds) or element of the built environment (e.g., septic systems).

This project aggregated several studies conducted by the authors over the past decade into a unified ecological risk assessment of the likely effects of SLR on the ecosystem services provided by the IRL using a suite of living (n = 2) and built (n = 3) elements of the watershed. The assessment utilizes NOAA (2024) scenario-based, site specific SLR trajectories to model submergence and establishes a likely time-frame over which the ecosystem services considered will be compromised. The results are organized to convey trends in vulnerability over time at a spatial scale that can be utilized by coastal zone practitioners to (re)evaluate existing adaption action plans and (re)prioritize project implementation based upon the results of submergence simulations in 2050, 2070, and 2100. This approach is broadly applicable to other estuaries at risk of climate change and SLR.

Study Area

This project focused on a 250 km long shore-parallel micro-tidal estuary located within the east-central Florida barrier island complex (Figure 1). It covers an area of 353 km^2 and is composed of three distinct and connected water bodies: the Indian River, Banana River, and Mosquito Lagoon. Water depths average about 2 m and historically the bottom was covered by extensive seagrass that has since declined within all three basins because of the deterioration of water clarity (Steward et al., 2005). Most of the IRL's tidal wetlands were filled, ditched, or impounded over the past century (Brockmeyer et al., 2021). Those that remain are located primarily in large land conservation areas (e.g., Merritt Island National Wildlife Refuge; Figure 1), mosquito control impoundments or smaller, locally managed conservation areas. In the southern and central portion of the IRL, the wetlands consist of mangrove-dominated plant communities that transition northward into salt marsh. Its 2,284 km^2 humid subtropical watershed sprawls over five coastal counties. The lagoon's total annual economic contribution to the region is estimated to be about ten billion dollars and is generated in part by the ecosystem services it provides, including fishing and ecotourism (East Central Florida Regional Planning Council and Treasure Coast Regional Planning Council, 2016). Hence there is keen interest in restoring and sustaining the ecological value and function of the IRL.

Parkinson and Wdowinski (2023) report sea level rise along the east central coast of Florida has accelerated from 6.4 ± 0.6 mm yr^{-1} (1993 to 2002) to 9.6 ± 1.6 yr^{-1} (2003 to 2022). The rate of rise over the past decade falls between NOAA's scenario-based intermediate high and high trajectories (NOAA, 2024). Given there continues to be no substantial progress towards limiting carbon emissions (United Nations Environmental Program, 2024), the rate of SLR is expected to continue accelerating over the duration of this century.

Methods

This project began by compiling a suite of natural and built components of the watershed that either contribute to (e.g., seagrass) or impede (e.g., nutrient pollution from OSTDS) estuarine ecosystem services. The latter are considered ecosystem service proxies. These were then subjected to a submergence simulation using *Future Shorelines*, an on-line geospatial application developed as a decision support tool for coastal practitioners (Juhasz et al., 2023; Parkinson et al., 2024). In this study, the scenario-based median high SLR trajectory of NOAA (2024) was used to model conditions in the years 2050, 2070, and 2100. Five natural or built components of the estuary were selected for evaluation.

Recreational and commercial boating

There are no systematically collected data on the use of the IRL by recreational boaters (e.g., fishing, sport activities, nature-based tourism). However, casual inspection of the number of boats on the water or trailers parked at public boat ramps on any given day indicates this activity is very popular. In a recent study, Adams et al. (2024) report that 1,322 licenses were issued to commercial fishers in the study domain in 2023. Their catch that year was more than 700 tons. Both activities contribute to the local economy and resident quality of life. To quantify the potential impact of SLR on recreational and commercial boating, the inundation of public motorized boat ramp parcels was quantified. Ramp location data were acquired using the on-line portal created by the Florida Fish and Wildlife Conservation Commission (n.d.). At each time-step, the effect of sea level rise on ramp services was visually classified as follows: (a) partially submerged; lower elevation of ramp inundated, but site still functional, (b) largely submerged; ramp and portions of the parking lot submerged; site is no longer functional, and (c) submerged; entire facility submerged (Figure 2).

Spoil islands

There are 212 spoil islands located in the IRL (Florida Medical Entomology Laboratory, 2024). These were created from dredge material during the construction of the Intracoastal Waterway and have evolved into ecological communities which significantly contribute to the biodiversity of the IRL (Florida Coastal Office, 2016). Based upon biological surveys, a Spoil Island Management Plan was created (Florida Bureau of Aquatic Preserves, 1990) for islands located in the IRL Aquatic Preserve (IRLAP) that extends from southern Brevard County to the Ft. Pierce inlet in St. Lucie County (Figure 1). The plan includes 76 islands, each designated for "an appropriate use" or ecosystem service: recreation, conservation, or critical wildlife area. Most islands are <2 m above present sea level and vulnerable to SLR.

To quantify the potential impact of SLR on spoil island ecosystem services, inundation was quantified using location maps and service delineation data provided by Friends of the Spoil Islands (2024). The impact of SLR on island ecosystem services was based upon the extent of submergence relative to the island's present area (m^2): the larger the land loss, the greater the impact. Because the current version of the *Future Shorelines* tool is not configured to allow on-screen length measurements, island inundation generated by the tool at each time step was estimated in Google Earth and rounded to the nearest 100 m^2. The following classification hierarchy was utilized to quantify disruption: (a) partially submerged; <30% of the island is submerged; (b) largely submerged; 30 to 80% of the island submerged, (c) submerged; >80% of island submerged (Figure 3). The definition of the submerged category is designed to account for shoreline erosion and land loss for the time-interval being evaluated. The presence of windward wave cut scarps and leeward prograding (i.e., accretionary) sandspits indicate the islands are in dynamic equilibrium with the prevailing wave climate that has over time reduced elevation and area above sea level. A simple time-series analysis of one arbitrarily selected island (IR35) provides additional justification for this definition. Between the years 1994 and 2023, the average rate of IR35 land loss averaged 300 m^2 yr^{-1}. Therefore, this island will likely lose an estimated 10,000 m^2 between 2050 and 2070. But this value is greater than the estimated area of the island in year 2050 (5,000 m^2; Supplemental Table 1). Hence, the island will very likely be underwater in 2070. Rates of land loss were quantified on several other islands to substantiate this assumption.

On-site treatment and disposal systems

Septic systems or OSTDS located in low-lying areas of the coastal zone are especially vulnerable to SLR since they are installed below grade. As water levels rise, the undersaturated zone or storage space of the drain field (i.e., zone of discharge, percolation, and treatment) is reduced or eliminated (c.f., Decker, 2022). This can ultimately lead to system failure and the release of pollutants (e.g., nutrients, pathogens) to the groundwater system, surface waters, and/or coastal waterways (c.f., Miami-Dade County Department of Regulatory & Economic Resources, 2018). Evidence that these systems contribute to IRL pollutant loading under present environmental conditions has recently been documented (Barile, 2018; Herren et al., 2021) and can result in impairment of water quality, eutrophication, harmful algal blooms (HAB) and related ecosystem services (Herren et al., 2021; Lapointe et al., 2015; Troxell et al., 2022). Hence, in this study, OSTDS are considered a built ecosystem service proxy that is vulnerable to SLR.

To quantify the potential impact of OSTDS failure caused by SLR, inundation was quantified using geospatial data obtained from the Florida Department of Health (2024). These data include the locations of known and likely septic systems at the parcel level. The precise location of the systems on the parcel and inverted elevations of the tank and drain field are typically not known. System failure or submergence was assigned when the extent of inundation corresponding to a future SLR scenario spatially intersected a parcel's location and elevation (Figure 4).

Wastewater treatment plants

As noted by Hummel et al. (2018), WWTP (i.e., the processing facility) are typically located at low elevations near the coastline to minimize the cost of collection and discharge, making them vulnerable to rising water levels. So too and perhaps even more so, are the lateral and main sewer lines of the sanitary system that convey wastewater from the source to the treatment facility because they are generally installed below grade level. Since WWTP are designed to process a certain quantity of sewage, the added water associated with a heavy rainfall event or exceptional tide can overload the collection system and reduce treatment efficiency (Flood and

Cahoon, 2011). For example, during Hurricane Ian (2022), the Brevard County's South Beaches facility (Figure 1, Site e) was forced to discharge millions of gallons of partially treated sewage into the IRL because inflow volumes exceeded the facility's design. According to the Marine Resources Council (Marine Resources Council, 2024), there were 168 wastewater spills into the IRL watershed between August 1st 2023 and July 31st 2024. As water levels rise, so too will the frequency, extent, and duration of WWTS design exceedances. These exceedances can result in water quality degradation, eutrophication, HABs, and a decline in related ecosystem services (Lapointe et al., 2015). This study focused on the WWTP, not the upstream conveyance system. At each time-step, the effect of SLR on each of the WWTPs was visually classified as follows: (a) no flooding; sea level did not inundate above-ground elements of the facility, (b) partial submergence; some flooding but no inundation of above ground facilities or infrastructure, (c) largely submerged; elements of the facility are flooded to the extent that is its function or access is impacted, (d) submerged; >80% of the facility is flooded and non-functional (Figure 5).

Seagrass

Seagrasses are among the most productive coastal ecosystems in the world (Duffy, 2006). They provide many ecosystem services including habitat to native species, nursery areas for commercial and recreational fisheries, buffer to storm-induced shoreline erosion, stabilization of sediment, and blue carbon sinks (McHenry et al., 2023). Their distribution is largely controlled by the availability of light and that light-dependent boundary is called the deep(water) edge. In the IRL, the deepwater edge is referred to as the median depth limit or MDL (Steward et al., 2005). Evidence supporting the hypothesis of an inverse relationship between SLR and seagrass coverage as advanced by Seidel and Parkinson (2014, 2013) and as postulated in this study was recently presented by Capistrant-Fossa and Dunton (2024). They demonstrated that seagrass populations in the western Gulf of Mexico have been in decline since 2014 in response to SLR. As the water depth increases, the MDL migrates upslope resulting in a reduction of seagrass coverage.

The MDLs and distribution of seagrass in the IRL have been systematically mapped throughout the study domain since 1986 (Morris et al., 2022; Steward et al., 2005; Virnstein et al., 2007). The MDLs are grouped into 19 distinct areas or seagrass segments, each defined by a unique value. Eighteen of those segments are in the study domain. The effect of SLR on the ecological services of seagrass at each time step was modeled by assuming losses along the deepwater edge and gains in upland natural areas submerged by shoreline transgression. The submergence simulations used in this study were generated by Seidel and Parkinson (2014, 2013) using data provided by the St. Johns River Water Management District (i.e., seagrass maps generated in 2009, bathymetric and topographic digital elevation models or DEMs) and the University of Florida (i.e., Florida Natural Areas Inventory 2012). Their analysis included two SLR simulations that were considered in this study: (1) 0.6 m (2 ft) in 2050 and (2) 1.2 m (4 ft) in 2100. At each SLR time-step, changes in the aerial extent of seagrass in each segment were quantified. The model assumed the MDL and DEMs remained constant relative to the initial or starting condition. Seagrass loss was proportional to the magnitude of SLR and existing bathymetric relief. Gains in seagrass distribution were estimated along the transgressing estuarine shoreline by calculating the area of natural land located between the original and new shoreline location. Gains in coverage were proportional to the magnitude of SLR, shoreline gradient upland topography, and the presence of upland natural areas.

Sea level rise

Submergence simulations were generated using *Future Shorelines*, an on-line geospatial tool that emulates shoreline transgression over the existing landscape (Juhasz et al., 2023; Parkinson et al., 2024) using DEMs acquired from the 3DEP Peninsular Florida LiDAR Project (Florida Geographic Information Office, 2019) and the mean higher-high water (MHHW) surface from NOAA's VDatum tool (NOAA, 2023). Sea level rise is emulated using median NOAA scenario-based SLR trajectories at Port Canaveral (Figure 1). All elevations are relative to year 2000. The tool provides an option to select one of four-time steps (i.e., 2030, 2040, 2050, 2100) and one of four scenarios: intermediate-low, intermediate, intermediate-high, and high. However, given the observed 21st century rates of rise along the east-central Florida coast and the persistent emissions gap, this investigation only considered the median NOAA high SLR trajectory at three-time steps; 2050, 2070, and 2100. The *Future Shorelines* tool does not currently include a SLR time-step in 2070. In this study, the sea level elevation in 2070 was emulated using the NOAA intermediate SLR scenario in 2100. This value (1.1 m) falls within the range uncertainty in 2070 corresponding to the NOAA high scenario (0.7 to 1.2 m; Table 1) and is therefore considered an acceptable substitute for the purposes of this study. The *Future Shorelines* tool uses a passive approach to inundation in which there are no changes to the land surface elevation (i.e., bathtub model) over the duration of the study period. The model does not currently permit inundation in areas that are not hydraulically connected to the lagoon. There has been some recent criticism regarding the frequent use of the bathtub approach to predict flood risk because it is not a dynamic model (Sanders et al., 2024). These concerns are valid when the model has been applied to a dynamic landscape (e.g., meandering river floodplain, open ocean shoreline). The use of the bathtub model as a means of simulating submergence within the IRL is appropriate because the prevailing, non-stochastic processes that are responsible for its geomorphologic evolution operate over centuries to millennia (c.f. Parkinson, 1995). Hence, no substantial changes to the basin's bathymetry or topography are expected over the duration of time being considered in this investigation.

The seagrass data considered in this study (Seidel and Parkinson, 2014) were generated under two SLR scenarios: (1) 0.6 m (2 ft) in 2050 and (2) 1.2 m (4 ft) in 2100. The first scenario was used to model the effects of SLR on seagrass distribution in year 2050 as was originally modeled. This value falls within the likely range of sea level elevations projected by NOAA in that year (Table 1). Their second scenario, which was designed to emulate conditions in 2100, was used in this study to model seagrass distribution in year 2070. This is considered a reasonable approach since the 1.2 m (4 ft) rise used in the original analysis falls within the likely range of sea level elevations projected by NOAA in 2070 (Table 1).

The median NOAA SLR trajectories are bounded by lower (i.e., 17th quartile) and higher (i.e., 83rd quartile) estimates (Figure 6). This envelope is the likely range in elevation or uncertainty calculated at each time step. It also provides a means of estimating the uncertainty in the arrival time of sea level elevation corresponding to the target years 2050, 2070, and 2100. For example, the median trajectory suggests that in 2050 sea level is expected to reach an elevation of 0.5 m relative to 2000 (Table 1) and that value is bounded by a lower (0.3 m) and higher (0.6 m) estimate of sea level elevation. Conversely, the lower and higher trajectories can be used to determine the range of arrival times about the 2050 median elevation of 0.5 m. The lower trajectory suggests an elevation of 0.5 m won't be reached until 2057. The higher trajectory suggests it will arrive in 2043. So, the uncertainty of sea level reaching an elevation of 0.5 m in 2050 is +/- 7 yrs. The uncertainty in the arrival times of the median estimate of sea level elevation in 2070 and 2100 were also calculated as +8/-7 yrs in 2070 and +9/-6 years in 2100. To simplify the use of uncertainty estimates, we rounded up the uncertainty in the arrival time of the median elevation at each time step using the value of +/- 10 yrs.

The NOAA trajectories include an estimate of *regional* vertical land motion (VLM), which is an important component of SLR (Sweet et al., 2022). In the study domain, regional VLM is downward, and this serves to increase the rate of SLR relative to other regions where there is no motion or it is upward (e.g., glacial rebound). It has also been demonstrated that *local* downward VLM or subsidence can cause the rate of SLR to be faster than the NOAA regional projections (Fiaschi and Wdowinski, 2020; Wdowinski et al., 2020). This can result in the inundation of coastal areas earlier than predicted by the NOAA simulations and has been attributed to surface loading or displacement beneath high rises or other anthropogenic structures (Aziz Zanjani et al., 2024; Sharma et al., 2024). The submergence simulations of this study did not consider the effect of local subsidence. This is because two of the ecosystem attributes are natural (i.e., spoil islands, and seagrass) and not associated with anthropogenic structures. The other three (i.e., boat ramps, OSTDS, WWTP) are relatively small anthropogenic structures with minimal capacity to induce displacement of a sufficient magnitude to alter the results and coastal management applications of this study.

Results

Recreational and commercial boating

Forty-seven motorized boat ramps were identified in the study domain including 10 in Volusia County, 13 in Brevard County, 8 in Indian River County, 8 in St. Lucie County, and 8 in Martin County (Supplemental Table 2). In Volusia County (Figure 7) model simulations suggest 7 (70%) ramps will be partially submerged and 3 (30%) largely submerged by 2050. In 2070, all 10 ramps will be submerged. In Brevard County, by 2050 nine (69%) ramps will be partially submerged and 4 (31%) largely submerged. In 2070, 3 (23%) will be partially submerged, 2 (15%) will be largely submerged and 8 (62%) entirely submerged. By the end of the century, all 13 ramps will be submerged. In Indian River County, 6 (74%) ramps will be partially submerged, one (13%) largely submerged, and another completely submerged in 2050. In 2070, one (13%) ramp remains partially, and another largely submerged. Six (75%) will be submerged. By 2100, one (13%) ramp will be largely submerged and the other 7 (87%) submerged. In St. Lucie County, 6 (75%) ramps will be partially submerged and another 2 (25%) largely submerged in 2050. By 2070, 4 (50%) will be largely submerged and another 4 completely submerged. All ramps will be submerged in 2100. All 8 Martin County boat ramps will be partially submerged in 2050. By 2070, 2 (25%) remain partially submerged, while 5 (62%) will be largely submerged and one (13%) completely submerged. In 2100, one will remain largely submerged while all others (88%) will be submerged. In summary, for the entire study domain, the results indicate that by 2050, 23% (n = 11) of the 47 ramps will either be largely or entirely submerged. In 2070, this increases to 87% (n = 41), including all ramps in Volusia County (n= 10) and St. Lucie County (n = 8). In in 2100 all but two ramps will be completely submerged.

Spoil islands

This study evaluated 76 spoil islands that are in the section of the IRLAP extending from southern Brevard County to the Ft. Pierce Inlet in St. Lucie County. Each of these islands has been designated by the Florida Department of Environmental Protection to provide a specific ecosystem service (i.e., recreation, conservation, critical wildlife area; Supplemental Table 3). In southern Brevard County (Figure 8), 6 (38%) of the islands will be partially submerge, 3 (19%) largely submerged and 7 (44%) completely submerged by 2050. In 2070, 7 (44%) of the islands will be largely submerged and 9 (56%) submerged. By 2100, 3 (19%) will be largely submerged and the remaining 13 (82%) underwater. By 2050 in Indian River County, 3 (8%) of the islands will be partially submerged, 13 (34%) largely submerged and the remaining 22 (58%) submerged. In 2070, one island (3%) will be largely submerged and the other 37 (97%) completely submerged. In 2100, all 38 spoil islands will be submerged. In St. Lucie County, one (5%) of the islands will be partially submerged by 2050, 8 (36%) largely submerged and the other 13 (59%) submerged. In 2070, one (5%) of the islands will be largely submerged and the other 21 (95%) under water. In 2100 all 22 spoil islands will be submerged. In summary, the results indicate that by 2050, 53 (70%) of the 76 IRLAP spoil islands considered in this investigation will either be largely or entirely submerged. This includes 29 (83%) of the spoil islands designated as recreational, 36 (90%) of the conservation islands and the only island designated as a critical wildlife area (Figure 9). By 2070, none of the spoil islands will be functioning according to their designated service.

On-site treatment and disposal systems

According to the data considered, 11% (n = 27,121) of all known or likely OSTDS in the five-county area are located within the IRL watershed on parcels with elevations at or below the NOAA sea level high trajectory elevation in year 2100 (Supplemental Table 4). In this investigation, OSTDS inundation in 2050 and 2070 is expressed relative to those that will be submerged by 2100. In Volusia County (Figure 10), 1,251 (21%) of the OSTDS parcels will be submerged by 2050. In 2070, 1,709 (28%) will be submerged. In Brevard County, 3,841 (33%) of the systems will be submerged in 2050 and 6,673 (58%) by 2070. By 2050, 577 (30%) of the OSTDS considered in this study will be submerged in Indian River County. In 2070, that value increases to 1,922 (47%). In St. Lucie County, 1,846 (47%) of the OSTDS will be inundated by

2050. In 2070, the number increases to 3,898 (62%). In Martin County, 1,354 (37%) septic systems will be submerged by 2050. By 2070, 3,649 (55%) will be inundated. In total, 8,869 (33%) of the OSTDS that are known or likely to exist in the study domain will be submerged in 2050. In 2070, 13,725 (51%) will be below sea level.

Wastewater treatment plants

The on-line search indicated there are eleven WWTP in the study domain (Figure 1, Supplemental Table 5). In Brevard County (Figure 11), none of the plants will be affected by SLR in 2050. One (20%) of the 5 facilities will be largely submerged and another submerged by 2070. In 2100, one (20%) will be partially submerged, another largely submerged, and 3 (60%) will be submerged. In Indian River County, one of three facilities (33%) will be partially submerged by 2070 and then completely submerged in 2100. In St. Lucie County, one of the two facilities will be largely submerged in 2070 and by the end of the century, both will be submerged. There is one WWTP in Martin County and that facility remains emergent through the end of this century. In summary, none of the 11 WWTP considered in this investigation will be impacted by SLR in 2050. In 2070, seven remain above sea level (64%), while one (9%) will be partially submerged, two (18%) largely submerged, and one completely submerged. By 2100, three (27%) will remain above sea level, one (9%) will be partially submerged, another largely submerged, and six (55%) completely submerged.

Seagrass

Of the 18 seagrass segments considered in this study, two overlapped the boundaries between Volusia County and Brevard County (i.e., ML3-4) and between Brevard County and Indian River County (i.e., IR14-15). Therefore, the acreage of each segment was evenly split between the two adjoining counties (Supplemental Table 6). In Volusia County (Figure 12), the amount of seagrass in 2050 relative to the starting condition (4,203 ha) will be 2,464 ha (59%). By 2070, there will be only 1,807 ha or 43% of the original area. In Brevard County, the amount of seagrass in 2050 relative to the starting condition (22,231 ha) will be 14,643 ha (66%). By 2070, 23,880 ha will be present or 107% of the original area. In Indian River County, the amount of seagrass in 2050 relative to the starting condition (2,330 ha) will be 1,969 ha (85%). By 2070, there will be an estimated 1,577 ha or 68% of the original area. For the entire study domain, the amount of seagrass in 2050 relative to the starting condition (28,763 ha) will be 19,075 ha or 66%. By 2070, that number increase to 27,263 ha or 95% of the original seagrass area.

Discussion

The submergence simulations performed during this analysis suggest the effect of SLR on IRL ecosystem services will be substantial, widespread, and evident within 25 years. In the discussion that follows, the largely submerged and submerged data were combined for all groups except seagrass since both terms describe site conditions in which an ecosystem service is no longer functioning (Figure 13). Without intervention, the recreational and commercial ecosystem services provided by public boat ramps will be substantially compromised by 2070 as 87% will not be functional. Mitigating these losses on-site (e.g., ramp redesign, elevating the parking lot) may provide a near term solution, but will not be a permanent solution since water levels are expected to continue rising throughout the century. Furthermore, these improvements may not alone reconcile the loss of use if off-parcel access roads that provide ingress and regress are inundated. Relocation would appear to be the only permanent remedy. By 2050, 87% of the spoil islands considered in this evaluation will no longer provide recreational, conservation, or critical wildlife services. Mitigation options could initially include reducing shoreline erosion using nature-based solutions or the placement of fill to increase island elevation. Nature-based solutions have been installed on several of the islands not considered in this study (e.g., Bird Island, Martin County), but these have not proven effective in part because the installations are not capable of keeping pace with SLR. Fill placement is expensive and would likely be challenging to permit on all but the recreational islands. Therefore, it would appear likely that all of the ecosystem services provided by the spoil islands will be lost within the next 25 years.

One-third of the known or likely OSTDS parcels will be partially to completely below sea level by 2050 and half by 2070. But the impact on estuarine ecosystem function caused by OSTDS inundation and the release of nutrient pollution will begin well before submergence of the parcels on which they have been constructed because they are installed below ground level. Sea level rise is projected to increase by one foot (0.3 m) over the next 25 yrs (Parkinson and Wdowinski, 2023) and every 10 years or less thereafter (Table 1). Hence, after 2050, for every foot below grade an OSTDS is located, failure can be expected to occur 10 years prior to the parcel inundation time steps considered in this analysis. This means the timeline for the release of OSTDS nutrient pollutants and related deleterious effects on ecosystem services developed in this study is a conservative estimate. The same is true for WWTP, of which 3 (27%) will be largely to completely submerged by 2070, because the network of laterals and municipal service lines that convey wastewater to the treatment plants are also located below grade. In recognition of risks to ecological services posed by OSTDS and WWTP, a range of mitigation projects have been completed or are underway including septic to sewer conversions (e.g., Port St. Lucie, St. Lucie County), WWTP upgrades (e.g., South Beaches WWTP, Brevard County; Figure 1, Site e) and the construction of new treatment facilities to replace those located along the shores of the lagoon (e.g., Vero Beach Sewer Plant and Ft. Pierce WTP, Indian River County; Figure 1, Sites h and i). Although an expensive and often lengthy process, it is critical that these efforts continue at an accelerating pace.

Seagrass meadows are predicted to contract by about one-third over the next 25 years due to the shrinking area of seabed above the MDL. This initial loss may be an overestimate because the starting condition of 28,763 ha (2009) used in this analysis is larger than the average area of seagrass measured between 2011 and 2021 (16,655 ha; Morris et al., 2022). Between 2050 and 2070, the distribution of seagrass expands to 95% of the baseline value. This is substantially driven by the overtopping of natural areas located in the Merritt Island National Wildlife Refuge (Figure 1) and to a subordinate degree, other undeveloped (e.g., mosquito control impoundments) or conservation lands managed by local (e.g., Indian River Land Trust, Brevard County Environmentally Endangered Lands Program), state (e.g., Florida Division of Parks and Recreation), and federal agencies. By 2070, the likely rise in sea level (i.e., median 1.0 m, range 0.7 to 1.2 m; Table 1) will exceed the MDL in two of the seagrass segments (Figure 14; Supplemental Table 7). In 2080, this number increases to 9 and in 2090 the increase in sea level height will be greater than the MDL of all 18 segments. This suggests that after 2070, the horizontal accommodation space created by shoreline transgression onto natural areas will become the primary driver of seagrass resilience. To mitigate losses in the existing basin, projects constructed to improve water quality and clarity (e.g., septic to sewer conversions, living shorelines, seagrass restoration, stormwater diversion or treatment) must continue. These are designed to promote a deepening of the MDLs and a reduction in seagrass mortality caused by poor water quality (c.f., Morris et al., 2021; Steward and Green, 2007). Future gains in seagrass coverage are also possible in the natural lands that surround the basin. To ensure a successful transition from mangrove, salt marsh, or freshwater wetlands to seagrass meadows, land managers may have to *accept* changes that they have been *resisting* in the past in order to maintain a preconceived idea of the natural system under their jurisdiction (Schuurman et al., 2020).

The submergence simulation output and ecosystem service outcomes of this study are based upon several assumptions (i.e., no changes in bathymetry, topography or natural land use, constant MDL). As noted previously, changes in the bathymetry or topography over the duration of time being considered in this analysis are unlikely because the processes responsible for the IRL's geomorphology operate over centuries to millennia. Changes in natural land use are unlikely given they are held in the public trust for the purpose of conservation in perpetuity. Seagrass distribution has persistently declined over the past decade and those losses have been attributed to reductions in light availability (Morris et al., 2022), implying the MDLs are shallowing. Since the coverage values used in this study were acquired before then, the simulations may be initially overestimating ecosystem service loss.

It is important to acknowledge that this investigation did not consider the effect of stochastic processes on the IRL ecosystem and its services. Yet winter storms and hurricanes (i.e., winds, storm surge, rainfall deluge), freeze events, drought, and long intervals of elevated water temperature have been shown to disrupt ecosystem function or degrade habitat value (Feller et al., 2015; Herren et al., 2021; Lapointe et al., 2015; Morris et al., 2022; Phlips et al., 2021). The cumulative impact of these processes can be reasonably expected to accelerate the spatial and temporal loss of ecosystem services as modeled in this study.

Conclusions

Submergence simulations were conducted to evaluate the potential effect of SLR on Indian River Lagoon ecosystem services using the on-line geospatial tool *Future Shorelines*. Sea level rise was emulated using NOAA's median high scenario-base trajectory at three-time steps: 2050, 2070, and 2100. The error in the arrival time of each trajectory is +/-10 years. Five ecosystem services or their proxies were considered: boat ramps, spoil islands, OSTDS, WWTP, and seagrass. Results indicate substantial degradation in ecosystem services as early as 2050. The investigation did not consider the presence of groundwater or the impact of stochastic events that will hasten the pace and scale at which the IRL's ecosystem services are compromised. The outcomes of this study are therefore considered a conservative estimate of ecosystem service deterioration. Historical urbanization of the IRL watershed has resulted in the degradation of water quality, habitat value, and ecosystem function. To mitigate these impacts, numerous mitigation projects that have been completed, are underway, or are being planned throughout the watershed. This investigation suggests SLR will exacerbate existing risks and vulnerabilities to the ecosystem, making the goal of successful mitigation even more challenging and require a sustained commitment measured in decades.

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Data availability statement

The locations of boat ramps, spoil islands, on-site treatment and disposal systems (OSTDS) and wastewater treatment plants (WWTP) are available from https://doi.org/10.34703/gzx1-9v95/QYDD8Y.

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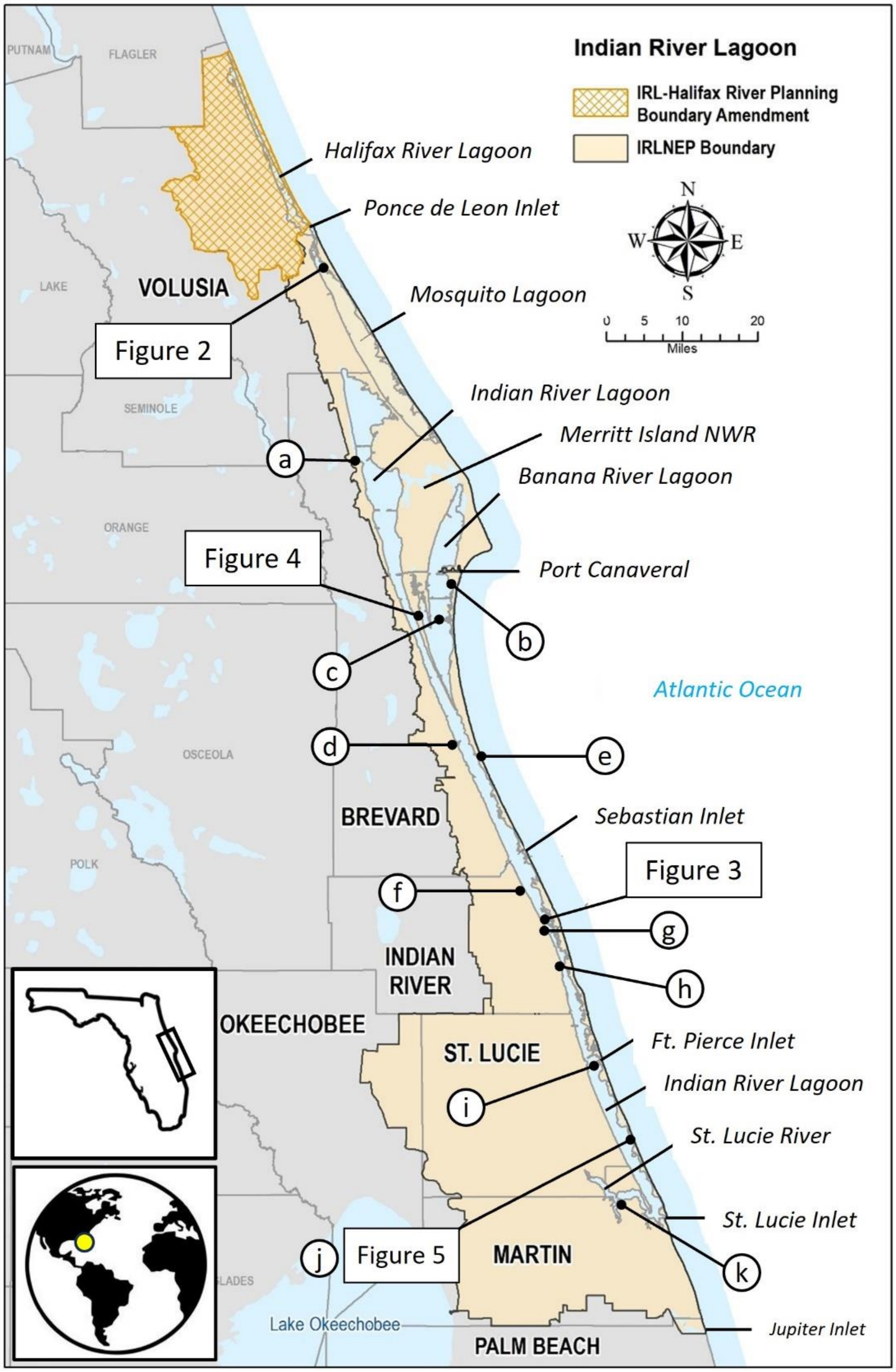

Figure 1. Regional location map of the study area. Circled letters indicate the location of wastewater treatment plants considered in this study. Geospatial data for all ecosystem services considered in this analysis can be found at https://doi.org/10.34703/gzx1-9v95/QYDD8Y. NWR = National Wildlife Refuge.

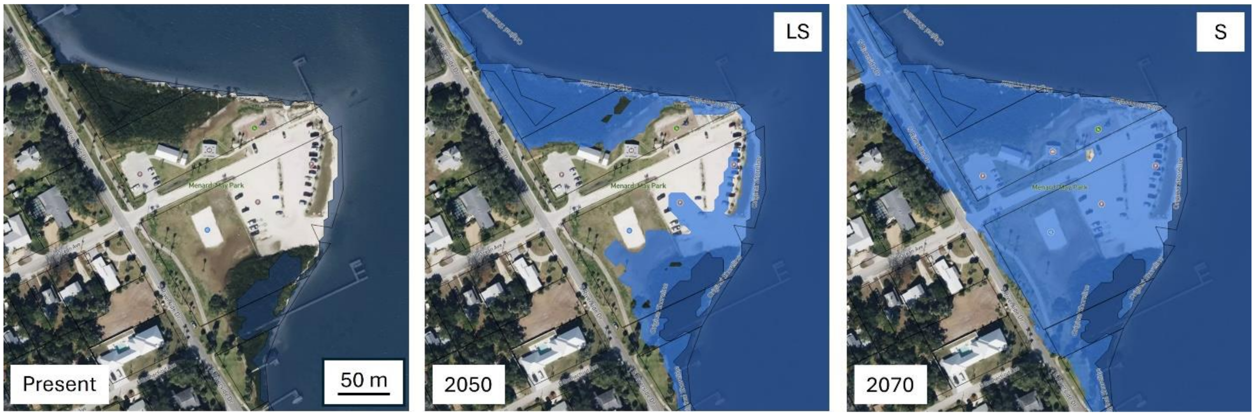

Figure 2. Submergence simulation of Menard May Park boat ramp, Volusia County. Left panel is present condition. By 2050 (center panel) the boat ramp will be largely submerged (LS) and in 2070 (right panel) the ramp will be completely submerged (S). See Figure 1 for location.

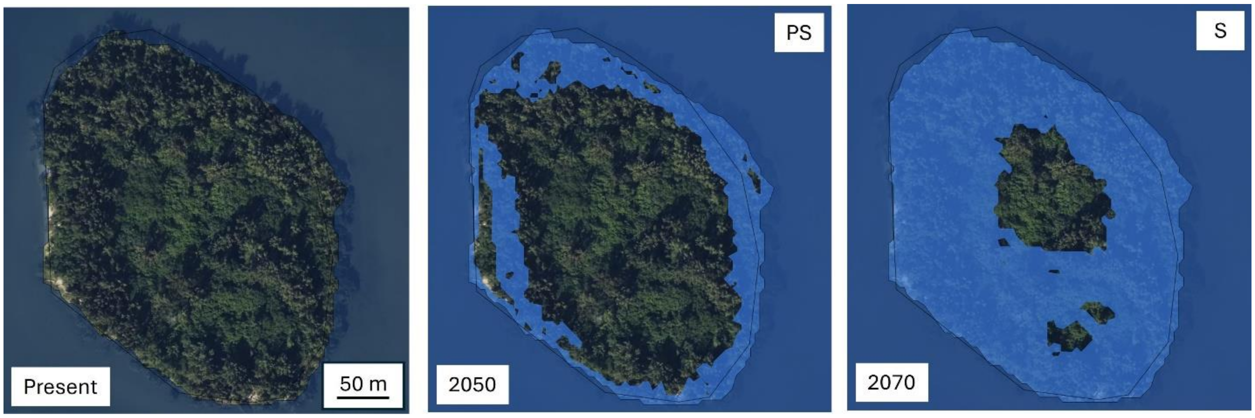

Figure 3. Submergence simulation of conservation spoil island IR35, Indian River County. Left panel is present condition. By 2050 (center panel) the island will be partially submerged (PS). Right panel is 2070 and indicates a portion of the island will remain emergent at that time. However, the island is classified as submerged (S) because the static or bathtub model used in the simulations does not account for area and elevation loss caused by wave erosion. See Figure 1 for location.

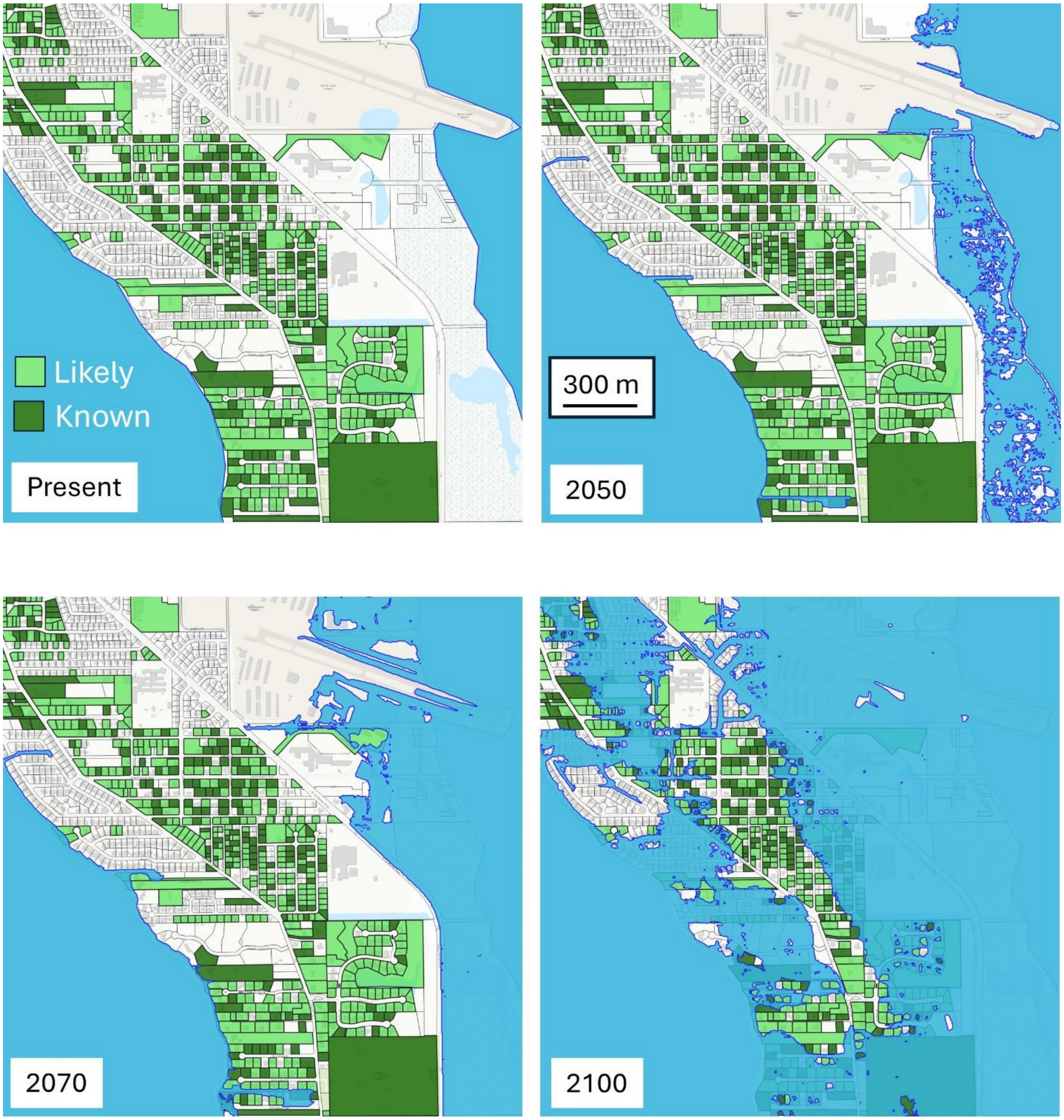

Figure 4. Submergence simulation of Merritt Island OSTDS (septic), Brevard County. Colored polygons indicate location of parcels in which the presence of an OSTDS has been confirmed (i.e., known) or is likely. Top left is present condition. In 2050 (top right), the eastern shoreline will experience some inundation (blue) but no parcels with OSTDS will be affected. In southwestern region, parcels located adjacent to a drainage canal will be partially submerged. In 2070 (bottom left) flooding along margins of the drainage canal network expands throughout the area but the impact to OSTDS is limited. By 2100 (bottom right), a substantial number of OSTDS parcels will be inundated. See Figure 1 for location.

Figure 5. Submergence simulation of the wastewater treatment plant SHIWWTF, St. Lucie County. Left panel is present condition. Center panel is 2050 and simulation suggests the plant will be partially submerged (PS). In 2070 (right panel) the plant will be largely submerged (LS). See Figure 1 for location.

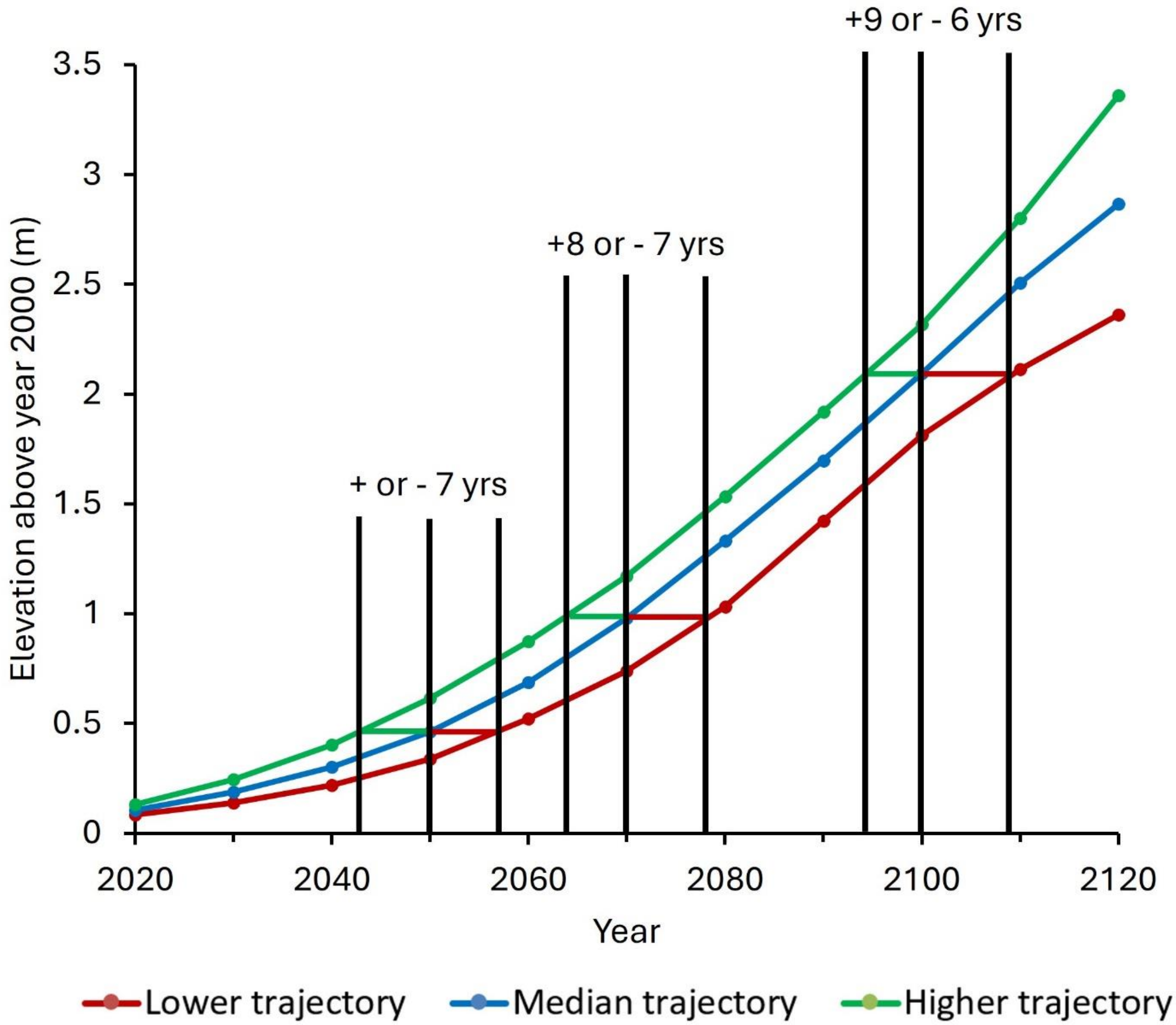

Figure 6. NOAA sea level rise trajectories for the high scenario. At each of the 3-time steps considered, extrapolations of the median elevation (see Table 1) to its intersection with the lower and higher trajectories yield the arrival time uncertainty for the target year.

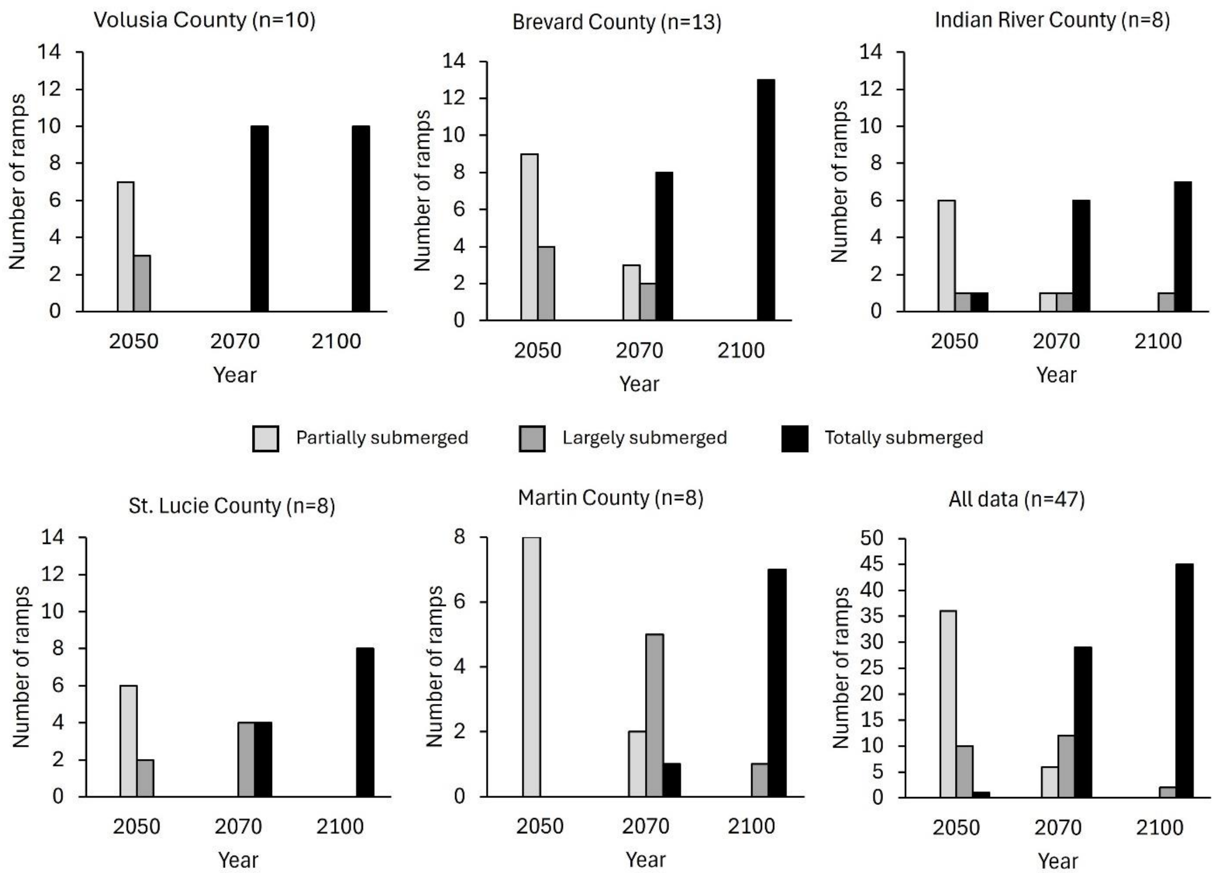

Figure 7. Results of boat ramp submergence simulations in each of the five counties considered and for the entire study domain. The recreational and commercial ecosystem services provided by a substantial number of ramps will be compromised by 2050 as many are partially (n = 36) to largely (n = 10) submerged. In 2070, more than half of the ramps (n = 29) will be completely submerged. In 2100 none are functional as they will be either largely (n = 2) or completely (n = 45) submerged.

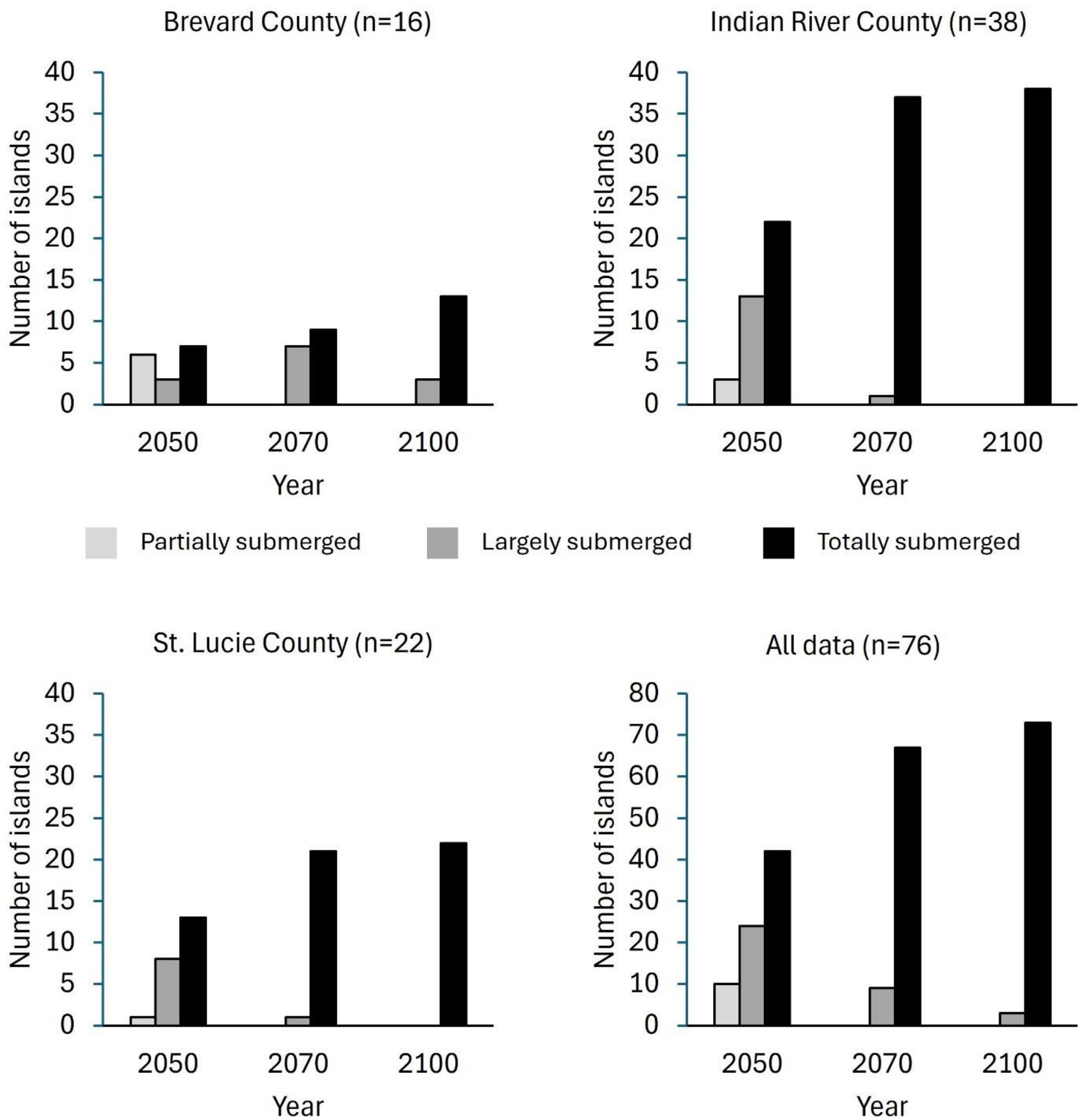

Figure 8. Results of spoil island submergence simulations in each of the three counties considered and for the entire study domain. In 2050, the ecosystem services provided by the islands (i.e., recreation, conservation, critical wildlife area) are substantially compromised as all but 10 will be largely (n = 24) to completely (n = 42) submerged. By 2070, none of the islands will be providing an ecosystem service as all are largely (n = 9) to completely submerged (n = 67).

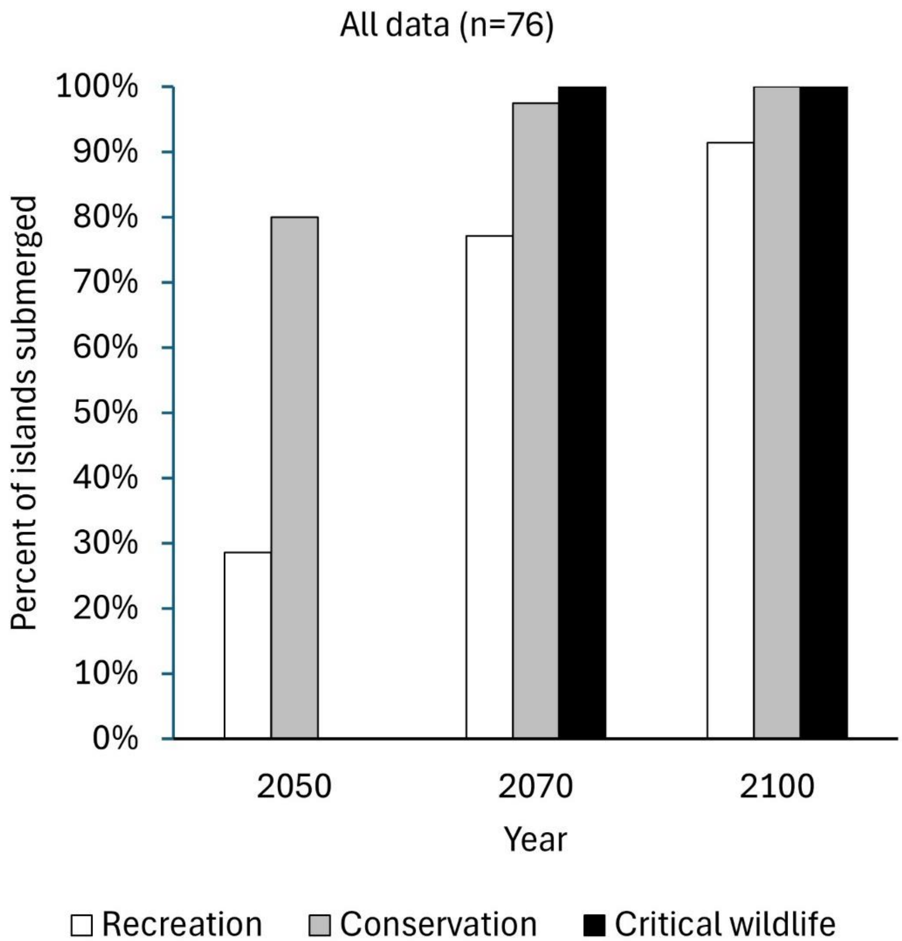

Figure 9. Results of spoil island submergence simulations organized by ecosystem service designation. By 2050, more than a quarter (n = 10) of the islands designated for recreational use will be submerged. Eighty percent (n = 32) of the islands recognized for their conservation value will be inundated by mid-century. In 2070, all the spoil islands except one designated for conservation and eight for recreation will be inundated.

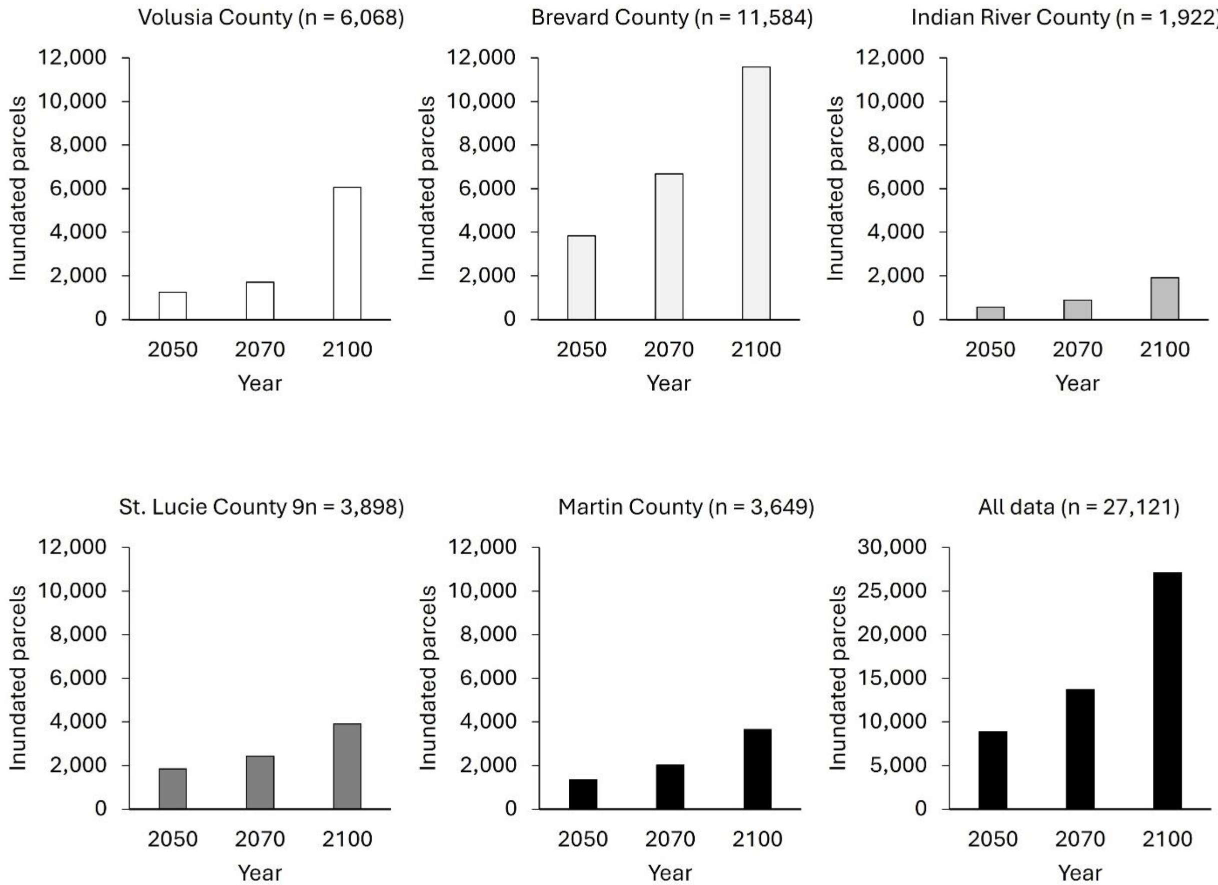

Figure 10. Results of OSTDS (septic) submergence simulations in each of the five counties considered and for the entire study domain. By 2050, 8,869 systems (33%) will be inundated, increasing the flux of untreated or partially treated wastewater into the basin. Nearly half (n = 3,841) of the submerged systems are in Brevard County. By 2070, the number of inundated OSTDS parcels increases to 13,725 (51%) with slightly less than half (n = 6,673) in Brevard County. All systems will be inundated by the end of the century.

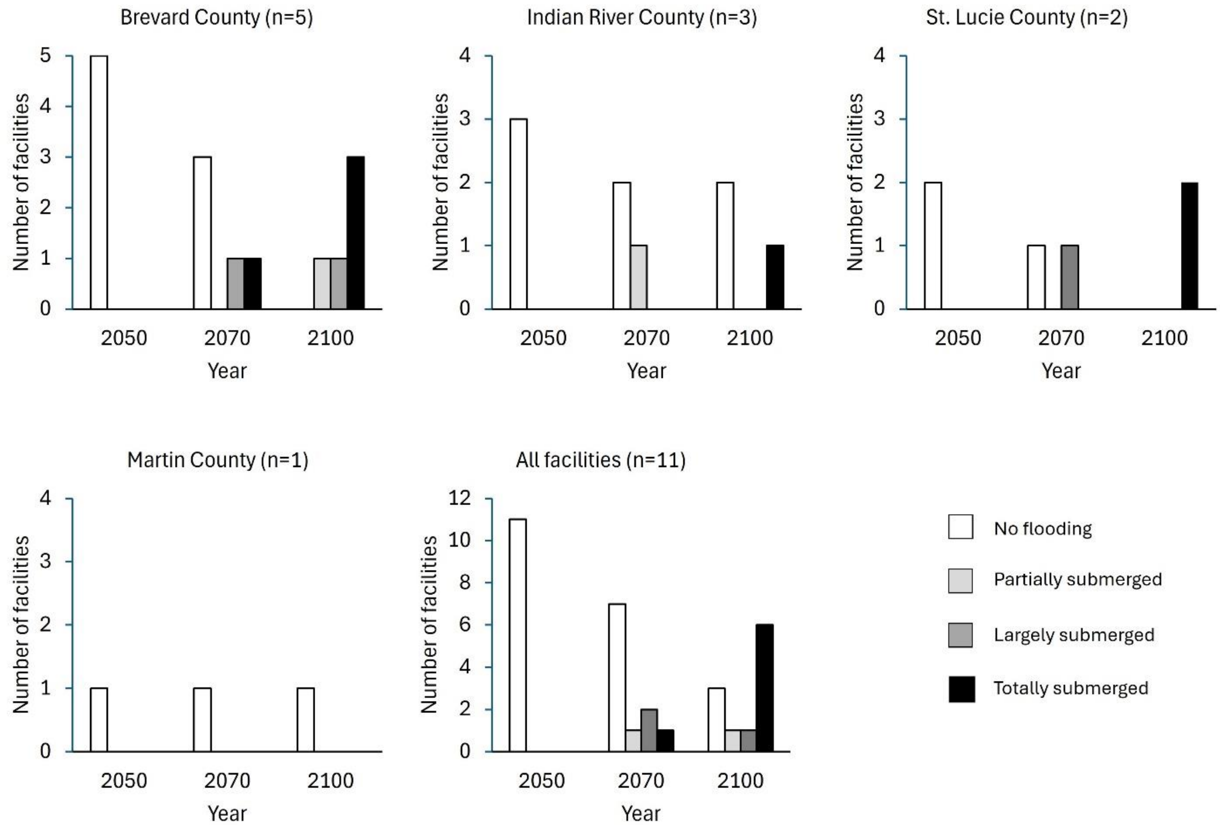

Figure 11. Results of WWTP submergence simulations in each of the four counties considered and for the entire study domain. No facilities were identified in the IRL watershed located in Volusia County. None of the facilities will be affected by sea level rise until 2070, when one will be partially submerged, two largely submerged and one totally submerged. Those experiencing at least partial flooding may release untreated or partially treated wastewater into the basin. By 2100, three of the eleven plants will not be subject to flooding, while the other eight will be partially or largely submerged (n = 2) or totally submerged.

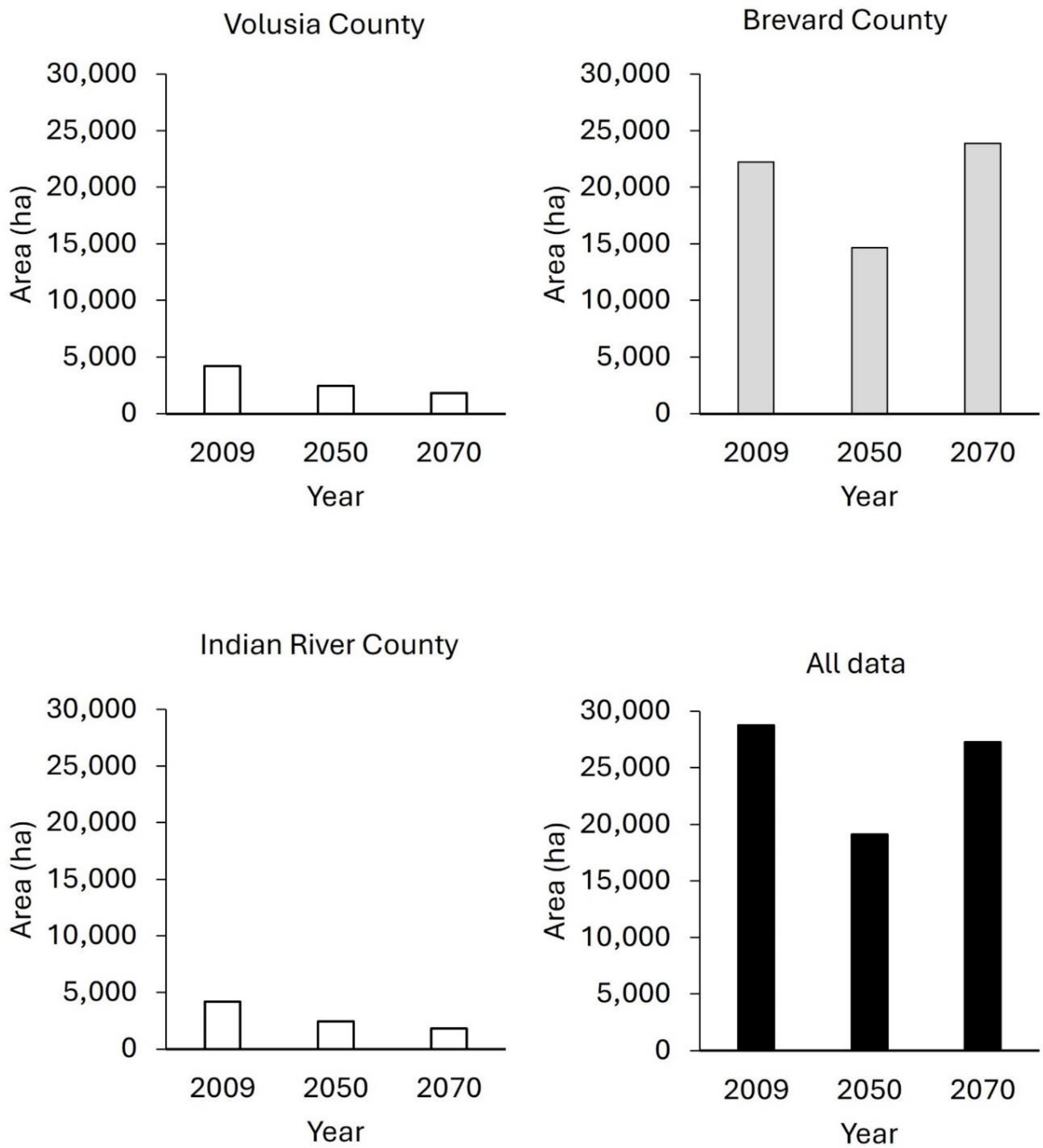

Figure 12. Results of seagrass submergence simulations for each of the three counties considered and for the entire study domain. The initial condition is 2009. In 2050, a decrease in seagrass distribution evident in all three counties, averaging 66% (19,075 ha) relative to the initial condition (28,763 ha). Over the next 20 years or by 2070, seagrass meadows are expected to continue shrinking in Volusia and Indian River County as deepwater losses exceed gains along the transgressing shoreline. In Brevard County, the presence of large expanses of natural land along the eastern shoreline (e.g., Merritt Island National Wildlife Refuge) provide more horizontal accommodation space for seagrass expansion than is lost along the deepwater edge. This will result in a change of 107% (23,880 ha) relative to the initial condition in 2070. The net result will be a change of 95% (27,263 ha) in 2070 relative to the basin-wide starting condition.

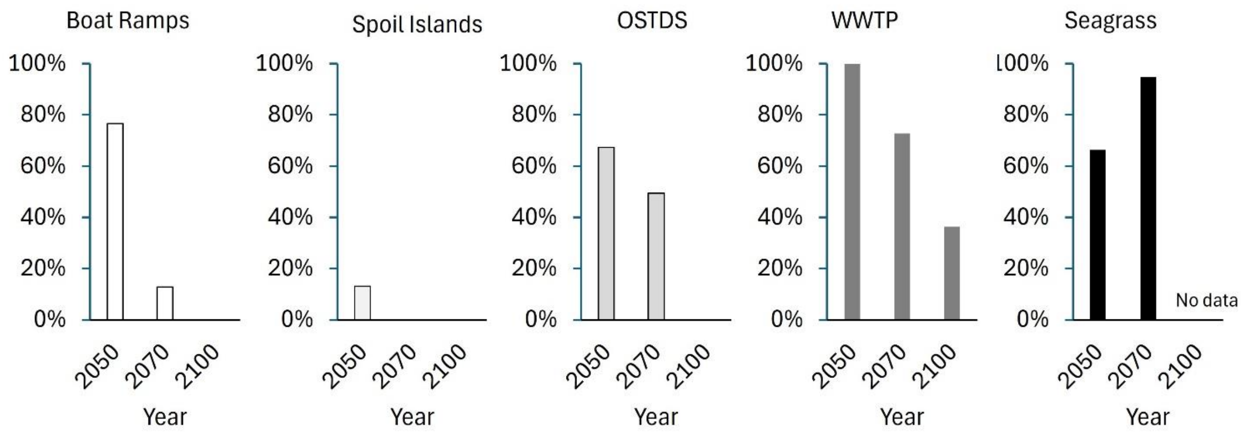

Figure 13. Percent of functional ecosystem service attributes (i.e., not flooded or only partially submerged) relative to starting condition. A persistent decline in all ecosystem service attributes except seagrass is expected concomitant with sea level rise.

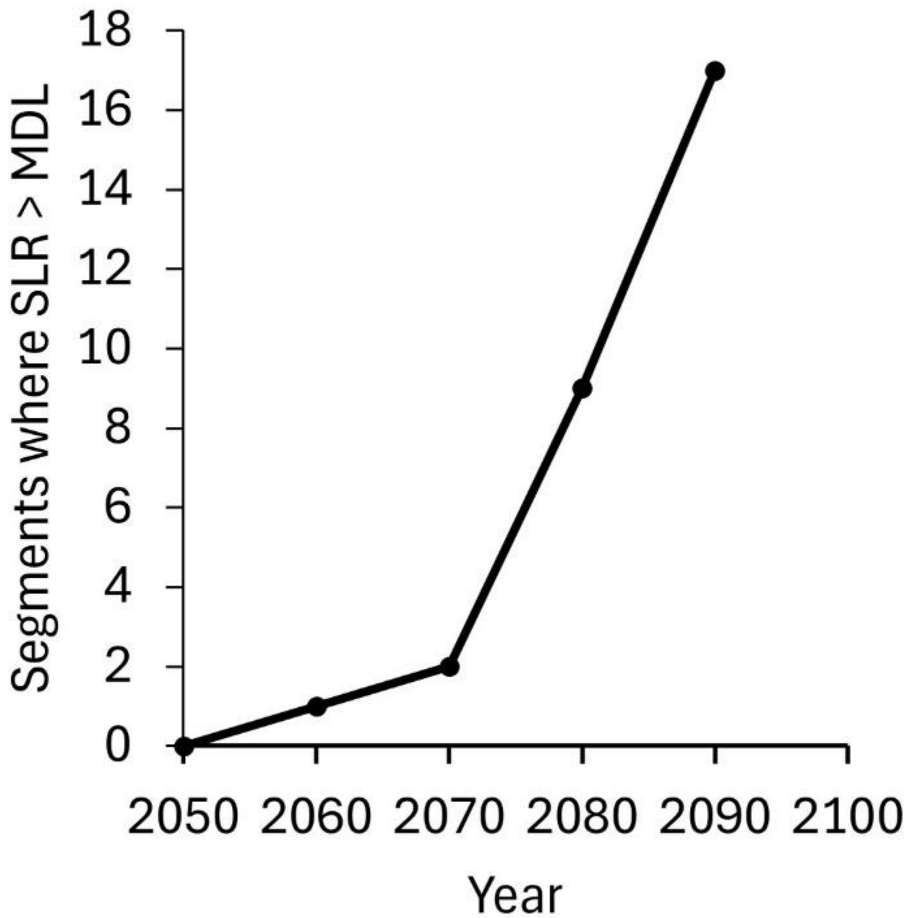

Figure 14. Number of seagrass segments in which the rise in sea level relative to the starting condition exceeds the MDL of that segment. This suggests the gains in seagrass coverage modeled between 2050 and 2070 will be lost during the last 30 years of the 21st century unless exceeded by the area of natural lands submerged by the lagoon's eastern transgressing shoreline.

Table 1

Table 1. Top. Observed rate of sea level rise (mm yr^{-1}) trends for the study area as recorded at the NOAA Triden
Canaveral, Florida. Error expressed as uncertainty. Middle. Range of sea level elevations in meters (ft) correspo
quartile), median, and higher (83rd quartile) trajectories at 10-year time steps to year 2100. Uncertainty in arrival
elevation in target years 2050, 2070, and 2100 relative to the median values are also shown (see Figure 6 for gra
data). Positive and negative values indicate elevation arrives later or earlier than median value, respectively. Dat
based trajectories relative to year 2000 at the Trident Pier station (NOAA , 2024). Bottom: Sea level elevation in
this investigation to simulate submergence. The *Future Shorelines* on-line geospatial tool does not consider year
median NOAA intermediate SLR elevation at year 2100 was used since it falls within the likely range of high-sc
projected in year 2070. See Figure 1 for the location of Trident Pier, Port Canaveral station.

Location	Observational period	Trend 1993-2022	Trend 2003-2022
Trident Pier	1994-present	6.42 ± 0.58	9.59 ± 1.64

Trajectory	Year 2040	2050	Uncertainty	2060	2070	Uncertainty	2080	2090	
Lower	0.2 (0.7)	0.3 (1.1)	+7 yrs	0.5 (1.6)	0.7 (2.4)	+7 yrs	1.0 (3.4)	1.4 (4.6)	1.
Median	0.3 (0.9)	0.5 (1.5)	na	0.7 (2.3)	1.0 (3.4)	na	1.3 (4.3)	1.7 (5.6)	2.
Higher	0.4 (1.3)	0.6 (2.0)	-7 yrs	0.9 (3.0)	1.2 (3.8)	-8 yrs	1.5 (4.9)	1.9 (6.2)	2.

	2050	2070	2100
Future Shorelines			
Intermediate			1.1 (3.4)
High	0.5 (1.5)		2.1 (6.9)
Seagrass	0.6 (2)	1.2 (4)	

Supplemental Table 1. Spoil island area data and submergence status assignments.

		Year									
		Present	2050			2070			2100		
County	Island[a]	Area m^2	Area	%loss	Status[b]	Area	%loss	Status	Area	%loss	Status
BC	BC36	1000	0	100%	S	0	100%	S	0	100%	S
	BC37	8500	6000	29%	PS	1060	88%	S	0	100%	S
	BC38	7000	5000	29%	PS	2200	69%	LS	745	89%	S
	BC39	500	0	100%	S	0	100%	S	0	100%	S
	BC40	2100	0	100%	S	0	100%	S	0	100%	S
	BC44a	14000	7500	46%	LS	6200	56%	LS	3800	73%	LS
	BC44b	14500	10500	28%	PS	7800	46%	LS	3000	79%	LS
	BC45	25300	16200	36%	LS	10000	60%	LS	500	98%	S
	BC46	28000	21000	25%	PS	10400	63%	LS	2400	91%	S
	BC47	12900	10200	21%	PS	8400	35%	LS	4800	63%	LS
	BC48	42000	31000	26%	PS	14900	65%	LS	4300	90%	S
	BC49	11900	4300	64%	LS	1600	87%	S	400	97%	S
	BC50	1500	0	100%	S	0	100%	S	0	100%	S
	BC51	1800	0	100%	S	0	100%	S	0	100%	S
	BC52	1700	0	100%	S	0	100%	S	0	100%	S
	BC53	7300	0	100%	S	0	100%	S	0	100%	S
IRC	IR1	10300	6400	38%	LS	0	100%	S	0	100%	S
	IR2	400	0	100%	S	0	100%	S	0	100%	S
	IR3	14000	7700	45%	LS	1900	86%	S	300	98%	S
	IR4	300	0	100%	S	0	100%	S	0	100%	S
	IR5	3300	500	85%	S	0	100%	S	0	100%	S
	IR6	19300	10100	48%	LS	1800	91%	S	800	96%	S
	IR8	800	0	100%	S	0	100%	S	0	100%	S
	IR9A	15000	10300	31%	LS	5000	67%	LS	0	100%	S
	IR9B	1500	0	100%	S	0	100%	S	0	100%	S
	IR10	3300	1000	70%	LS	0	100%	S	0	100%	S

	IR11	1500	0	100%	S	0	100%	S	0	100%	S
	IR12	3300	1200	64%	LS	0	100%	S	0	100%	S
	IR13	5300	3000	43%	LS	800	85%	S	0	100%	S
	IR14	5500	2800	49%	LS	500	91%	S	0	100%	S
	IR15	900	0	100%	S	0	100%	S	0	100%	S
	IR16	1200	0	100%	S	0	100%	S	0	100%	S
	IR17	900	0	100%	S	0	100%	S	0	100%	S
	IR18	1600	0	100%	S	0	100%	S	0	100%	S
	IR19	1400	0	100%	S	0	100%	S	0	100%	S
	IR21	29700	12000	60%	LS	0	100%	S	0	100%	S
	IR22	11700	900	92%	S	0	100%	S	0	100%	S
	IR23C	2400	1900	21%	PS	0	100%	S	0	100%	S
	IR25A	700	0	100%	S	0	100%	S	0	100%	S
	IR25B	700	0	0%	S	0	100%	S	0	100%	S
	IR25	28900	6500	78%	LS	0	100%	S	0	100%	S
	IR26A	1800	0	100%	S	0	100%	S	0	100%	S
	IR26B	1800	0	100%	S	0	100%	S	0	100%	S
	IR26	20200	15900	21%	PS	2400	88%	S	0	100%	S
	IR28C	1600	0	100%	S	0	100%	S	0	100%	S
	IR35	35800	26000	27%	PS	5000	86%	S	0	100%	S
	IR36	5100	500	90%	S	0	100%	S	0	100%	S
	IR37	19800	3200	84%	S	0	100%	S	0	100%	S
	IR38	10700	2300	79%	LS	0	100%	S	0	100%	S
	IR39	13800	0	100%	S	0	100%	S	0	100%	S
	IR40	17500	2100	88%	S	0	100%	S	0	100%	S
	IR41	23100	4500	81%	S	0	100%	S	0	100%	S
	IR42	28700	5800	80%	LS	1600	94%	S	0	100%	S
	IR43	20900	8200	61%	LS	2100	90%	S	0	100%	S
SLC	SL1	29200	6500	78%	LS	0	100%	S	0	100%	S
	SL1A	800	0	100%	S	0	100%	S	0	100%	S
	SL1B	280	0	100%	S	0	100%	S	0	100%	S

SL2	16100	3500	78%	LS	0	100%	S	0	100%	S
SL3	20100	4700	77%	LS	0	100%	S	0	100%	S
SL4	200	0	100%	S	0	100%	S	0	100%	S
SL5	25300	8000	68%	LS	2300	91%	S	0	100%	S
SL6	16800	4600	73%	LS	0	100%	S	0	100%	S
SL7	15300	3000	80%	LS	0	100%	S	0	100%	S
SL8	14900	2900	81%	S	0	100%	S	0	100%	S
SL9	2300	0	100%	S	0	100%	S	0	100%	S
SL10	2500	0	100%	S	0	100%	S	0	100%	S
SL11	21600	11300	48%	LS	2500	88%	S	0	100%	S
SL12	12900	5000	61%	LS	0	100%	S	0	100%	S
SL12B	300	0	100%	S	0	100%	S	0	100%	S
SL12C	500	0	100%	S	0	100%	S	0	100%	S
SL13	300	0	100%	S	0	100%	S	0	100%	S
SL13C	17300	10800	38%	LS	3300	81%	S	0	100%	S
SL14	26000	18500	29%	PS	9300	64%	LS	0	100%	S
SL14A	2100	0	100%	S	0	100%	S	0	100%	S
SL16	6500	0	100%	S	0	100%	S	0	100%	S
SL17	30900	14600	53%	LS	4200	86%	S	0	100%	S

BC = Brevard County. IRC = Indian River County. SLC = St. Lucie County.

[a]For locations go to https://doi.org/10.34703/gzx1-9v95/QYDD8Y.

[b]Submergance categories:

PS = Partially submergence. Lower elevation of ramp inundates, but site still functional.

LS = Largely submerged. Ramp and portions of the parking lot submerged; site is no longer functional.

S = Submerged. Entire facility submerged.

Orange infill = Island submergence simulation illustrated in Figure 3.

Supplemental Table 2. Boat ramp submergence simulation data.

N	County	Ramp[a]	Submergence assessment[b]								
			2050			2070			2100		
			PS	LS	S	PS	LS	S	PS	LS	S
	VC										
1		North Causeway West	1					1			1
2		North Causeway East	1					1			1
3		George Kennedy Memorial Park	1					1			1
4		Menard May Park		1				1			1
5		North Apollo Beach/Turtle Mound	1					1			1
6		Lake Side		1				1			1
7		Riverbreeze Park		1				1			1
8		Indian Mound Fish Camp	1					1			1
9		Lopez RV Park & Marina	1					1			1
10		Apollo Beach	1					1			1
	Sum		7	3	0	0	0	10	0	0	10
	BC										
11		WSEG Boat Ramp	1					1			1
12		Scottsmort landing	1					1			1
13		Playa Linda Beach		1				1			1
14		Titusville Marina		1				1			1
15		Kennedy Point	1			1					1
16		Kiwanis Island Park	1					1			1
17		Pineda Landing	1			1					1
18		Ballard Park		1				1			1
19		Front Street Park	1				1				1
20		Melbourne Beach	1				1				1
21		John Jorgensen's Landing	1					1			1
22		Christensons Landing	1			1					1
23		Sebastian Inlet North State Park		1				1			1
	Sum		9	4	0	3	2	8	0	0	13
	IRC										

24		Sebastian Inlet South State Park	1					1			1
25		Main Street	1			1				1	
26		Sebastian Municipal Yacht Club	1				1				1
27		Wabasso Causeway		1				1			1
28		MacWilliam Park	1					1			1
29		Riverside Park	1					1			1
30		Oslo Road			1			1			1
31		Round Island Park	1					1			1
	Sum		6	1	1	1	1	6	0	1	7
	SLC										
32		Village Marina	1					1			1
33		Ft. Pierce N Beach Causeway		1				1			1
34		Stan Blum Memorial	1				1				1
35		Fisherman's Wharf	1				1				1
36		S Causeway Island	1				1				1
37		IR Veterans Memorial	1				1				1
38		Jaycee Park		1				1			1
39		Blind Creek	1					1			1
	Sum		6	2	0	0	4	4	0	0	8
	MC										
40		Jensen Beach Causeway North	1					1			1
41		Jensen Beach Causeway South	1			1					1
42		Jensen Beach Indian Riverside Park	1				1				1
43		Stuart Causeway	1				1				1
44		Sheppard Park	1			1				1	
45		Charlie Leighton Park	1				1				1
46		Sandspirt Park	1				1				1
47		Owen Murphy Memorial	1				1				1
	Sum		8	0	0	2	5	1	0	1	7

[a]For locations go to https://doi.org/10.34703/gzx1-9v95/QYDD8Y.

[b]Submergance categories:

PS = Partially submergence. Lower elevation of ramp inundates, but site still functional.

LS = Largely submerged. Ramp and portions of the parking lot submerged; site is no longer functional.

S = Submerged. Entire facility submerged.

Orange infill = Facility submergence simulation illustrated in Figure 2.

Supplemental Table 3. Spoil islands submergence simulation data.

			Submergence assessment[c]																										
			2050			2070			2100			2050			2070			2100			2050			2070			2100		
County	Island[a]	Designation[b]	PS	LS	S	PS	LS	S	PS	LS	S	PS	LS	S	PS	LS	S	PS	LS	S	PS	LS	S	PS	SL	S	PS	LS	S
BC	BC36	C												1			1			1									
	BC37	R	1					1			1																		
	BC38	R	1				1				1																		
	BC39	C												1			1			1									
	BC40	R			1			1			1																		
	BC44a	R		1			1			1																			
	BC44b	R	1				1			1																			
	BC45	R		1			1				1																		
	BC46	R	1				1				1																		
	BC47	R	1				1			1																			
	BC48	R	1				1				1																		
	BC49	CW																				1				1			1
	BC50	R			1			1			1																		
	BC51	C												1			1			1									
	BC52	C												1			1			1									
	BC53	C												1			1			1									
Sum			6	2	2	0	7	3	0	3	7	0	0	5	0	0	5	0	0	5	0	1	0	0	0	1	0	0	1
IRC	IR1	R		1				1			1																		
	IR2	C												1			1			1									
	IR3	R		1				1			1																		
	IR4	R			1			1			1																		
	IR5	R			1			1			1																		
	IR6	R		1				1			1																		

IR8	C		1		1	1			1	1	1
IR9A	R	1		1		1					
IR9B	R					1					
IR10	R	1			1	1					
IR11	R		1		1	1					
IR12	R	1			1	1					
IR13	R	1			1	1					
IR14	R	1			1						
IR15	C								1	1	1
IR16	C								1	1	1
IR17	C								1	1	1
IR18	C								1	1	1
IR19	C								1	1	1
IR21	C							1		1	1
IR22	C								1	1	1
IR23C	C						1			1	1
IR25A	R		1		1	1					
IR25B	C								1	1	1
IR25	R	1			1	1					
IR26A	C								1	1	1
IR26B	C								1	1	1
IR26	C						1			1	1
IR28C	C								1	1	1
IR35	C						1			1	1
IR36	R		1		1	1					
IR37	C								1	1	1
IR38	C							1		1	1
IR39	C								1	1	1
IR40	C								1	1	1
IR41	C								1	1	1
IR42	R	1			1	1					

	IR43	R		1				1			1																		
Sum			0	11	6	0	1	16	0	0	17	3	2	16	0	0	21	0	0	21	0	0	0	0	0	0	0	0	0
SLC	SL1	C											1				1			1									
	SL1A	C												1			1			1									
	SL1B	C												1			1			1									
	SL2	R		1				1			1																		
	SL3	R		1				1			1																		
	SL4	C												1			1			1									
	SL5	R		1				1			1																		
	SL6	R		1				1			1																		
	SL7	R			1			1			1																		
	SL8	R			1			1			1																		
	SL9	C												1			1			1									
	SL10	C												1			1			1									
	SL11	C											1				1			1									
	SL12	C												1			1			1									
	SL12B	C												1			1			1									
	SL12C	C												1			1			1									
	SL13	C												1			1			1									
	SL13C	R		1				1			1																		
	SL14	C										1				1				1									
	SL14A	C												1			1			1									
	SL16	C												1			1			1									
	SL17	R		1				1			1																		
Sum			0	6	2	0	0	8	0	0	8	1	2	11	0	1	13	0	0	14	0	0	0	0	0	0	0	0	0

BC = Brevard County. IRC = Indian River County. SLC = St. Lucie County.

[a]For location and designation, go to https://doi.org/10.34703/gzx1-9v95/QYDD8Y.

[b]Ecosystem function designation: R = recreational (green), C = conservation (red), CW = critical wildlife area (purple)

[c]Submergance categories:

PS = Partially submergence. Lower elevation of ramp inundates, but site still functional.
LS = Largely submerged. Ramp and portions of the parking lot submerged; site is no longer functional
S = Submerged. Entire facility submerged

Orange infill = Island submergence simulation illustrated in Figure 3.

County	Present			Year								
				2050			2070			2100		
	Known	Likely	Total	Known	Likely	Total	Known	Likely	Total	Known	Likely	Total
Volusia	40023	48124	88147	740	511	1251	1044	665	1709	2941	3127	6068
Brevard	43452	30319	73771	1080	2761	3841	1780	4893	6673	2776	8808	11584
Indian River	31245	258	31503	559	18	577	21	876	897	1841	81	1922
St. Lucie	29977	5925	35902	1435	411	1846	1876	550	2426	2838	1060	3898
Martin	17102	3572	20674	1287	67	1354	1940	80	2020	3524	125	3649
All data			249997			8869			13725			27121

Supplemental Table 4. OSTDS submergence simulations. For location data go to https://doi.org/10.34703/gzx1-9v95/QYDD8Y.

Supplemental Table 5. WWTP submergence simulation data.

			Submergence assessment[b]											
			2050				2070				2100			
Figure 1 designation	County	Name[a]	N	PS	LS	S	N	PS	LS	S	N	PS	LS	S
a	BC	North WWTP	1				1							1
b		Cape Canaveral	1						1					1
c		Cocoa Beach	1							1				1
d		City of Melbourne	1				1						1	
e		South Beaches	1				1					1		
	Sum		5				3		1	1		1	1	3
f	IRC	Central WWTP	1					1			1			
g		Vero Beach Sewer Plant	1					1			S			1
h		South Regional WWTP	1				1				1			
	Sum		3				1	2			2			1
i	SLC	Ft. Pierce (existing)	1				1							1
j		SHIWWTF	1						1					1
	Sum		2				1		1					2
k	MC	Stuart WWTP	1				1				1			

BC = Brevard County. IRC = Indian River County. SLC = St. Lucie County.

[a]For locations go to: https://doi.org/10.34703/gzx1-9v95/QYDD8Y.

[b]Submergance categories:

N = No flooding.

PS = Partially submergence. Lower elevation of ramp inundates, but site still functional.

LS = Largely submerged. Ramp and portions of the parking lot submerged; site is no longer functional

S = Submerged. Entire facility submerged

Orange infill = Island submergence simulation illustrated in Figure 3.

Supplemental Table 6. Seagrass submergence simulation data.

County	Lagoon MDL segment	MDL (m)[1]	Area 2009	2050	2070
VC	ML1	nd	30	50	402
	ML2	0.8	1694	1448	273
	MI3-4 (1/2)	1.3	2479	966	1132
Sum			4203	2464	1807
BC	ML3-4 (1/2)		2479	966	1132
	BR1-2	1.8	4975	3842	4265
	BR3-5	1.6	4454	910	1281
	BR6	1.6	90	151	209
	BR7	1.4	117	81	117
	IRL1-3	1.6	3462	1973	5060
	IR4	1.6	291	314	784
	IR5	1.7	2218	3525	7382
	IR6-7	1.5	1875	815	2292
	IR8	1.6	208	124	98
	IR9-11	1.8	332	283	229
	IR12-13A	1.4	646	315	298
	IR13B	1.4	386	201	220
	IR14-15 (1/2)	1.3	698	1143	513
Sum			22231	14643	23880
IRC	IR14-15 (1/2)		698	1143	513
	IR16-20	1.2	968	573	616
	IR21	1.5	664	253	448
Sum			2330	1969	1577
Total			28763	19075	27263
Average		1.5			

VC = Volusia County. BC = Brevard County. IRC = Indian River County.

[1]Data from Steward et al. (2005).

Supplemental Table 7. Seagrass segment submergence below MDL simulation data. Sea level elevations derived from Table 1.

			Likely SLR (m)				
			2050	2060	2070	2080	2090
County	Segment	MDL (m)[1]	0.3 to 0.6	0.5 to 0.9	0.7 to 1.2	1.0 to 1.5	1.4 to 1.9
VC	ML1	nd					
	ML2	0.8		1	1	1	1
	MI3-4	1.3				1	1
BC	ML3-4						
	BR1-2	1.8					1
	BR3-5	1.6					1
	BR6	1.6					1
	BR7	1.4				1	1
	IRL1-3	1.6					1
	IR4	1.6					1
	IR5	1.7					1
	IR6-7	1.5				1	1
	IR8	1.6					1
	IR9-11	1.8					1
	IR12-13A	1.4				1	1
	IR13B	1.4				1	1
	IR14-15	1.3				1	1
IRC	IR14-15						
	IR16-20	1.2			1	1	1
	IR21	1.5				1	1
Sum			0	1	2	9	17

VC = Volusia County, BC = Brevard County, IRC = Indian River County.
[1]Data from Steward et al. (2005)