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

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Title Page

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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 urbanization, 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 (e.g., Puget Sound Partnership (WA), San Francisco Estuary Partnership (CA), Coastal Bend Bays and Estuaries Program (TX), Tampa Bay Estuary Program (FL) and Partnership for the Delaware Estuary (DE)). Accelerating SLR is expected to magnify those threats as they are gradually inundated (Parkinson, 2023). A similar causation of risk to estuarine ecosystem services has also been described throughout the world including Asia, Australia, Europe, India, and South America (Barletta et al., 2023; Grizzetti et al., 2021; Mitra et al., 2018; Statham, 2012; Suzzi et al., 2022;

Taillardat et al., 2020). 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 natural 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 natural (n = 2) and built (n = 3) elements of the watershed. The assessment utilizes NOAA (2024a) scenario-based, site specific SLR trajectories to model submergence in target years 2050, 2070, and 2100, and establishes a likely time-frame over which the ecosystem services 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 management plans and (re)prioritize project. Mitigation options to reduce risk are discussed for each of the five ecosystem services or their proxies evaluated in the study. Although is investigation was specifically designed to evaluate risks to IRL ecosystem services, the methodological approach utilized in the study is broadly applicable to other estuaries subjected to the deleterious effects urbanization, climate change and SLR (c.f., Medina et al., 2025).

Study Area

This project focused on the Indian River Lagoon; a 250 km long shore-parallel micro-tidal estuary located within the east-central Florida barrier island complex (Figure 1). The estuary 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 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 relative SLR along the central Atlantic 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 within NOAA's scenario-based intermediate high and high trajectories (NOAA, 2024a). 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 initially developed to assist IRL coastal resource practitioners identify installation locations where living shoreline resilience to SLR is optimized (Juhasz et al., 2023; Parkinson et al., 2024). In this study, the tool was repurposed to evaluate the effects of SLR on five IRL ecosystems attributes: (1) recreational and commercial boating, (2) spoil islands, (3) seagrass, (4) OSTDS, and (5) WWTP.

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 these activities are 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 and 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 SLR 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. The local relief of most islands is <2 m above present sea level.

To evaluate 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 simulated 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 both inundation and land loss to erosion at each time-interval; the latter deemed an important consideration given the widespread occurrence of windward wave cut island scarps and leeward prograding (i.e., accretionary) sandspits. These geomorphic features 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 land loss was 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 even if sea level elevation was stable during the 20 yr interval. 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 elevation 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 WWTP 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 was visually classified as follows: (a) no flooding; parcel not inundated, (b) partial submergence; some parcel 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 site access is impacted, (d) submerged; >80% of the facility is flooded and non-functional (Figure 5).

Seagrass

Seagrasses meadows 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 have been systematically mapped throughout the IRL 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 slope, upland topography, and the presence of upland natural areas.

Sea level rise

Sea level rise was modeled using NOAA scenario-based trajectories (NOAA, 2024a) at the Trident Pier, Port Canaveral (Figure 1). The NOAA trajectories represent the estimated plausible range for global SLR to 2150 and are bounded on the low end by a curve representing a simple extrapolation of the observed trend since the early 1990s and on the high end by a trajectory representing an extreme ice sheet melt/discharge scenario. All scenarios are emission-based, probabilistic projections relative to year 2000 (Sweet et al., 2022). NOAA used the global scenarios to derive regional relative sea level projections, like the one used in this study (i.e., Cape Canaveral). The regional projections incorporate estimates of vertical land motion (VLM), which in the study domain is downward (e.g., subsidence). The trajectories for Trident Pier include a uniform subsidence rate of 0.8 mm/yr, reflecting the modeled Glacial Isostatic Adjustment (GIA) rate for the southern US Atlantic coast (Kopp et al., 2014).

Submergence simulations were generated by *Future Shorelines* (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). The DEM has a horizontal resolution of 0.76 m and meets 3DEP Quality Level 3 (QL3) standards that require a vertical accuracy of ≤ 0.2 m (Stoker and Miller, 2022). The *Future Shorelines* tool provides an option to select one of four time-steps (i.e., 2030, 2040, 2050, 2100) and one of four NOAA 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 NOAA high SLR trajectory. In this study, three time-steps were considered: 2050, 2070, and 2100. The *Future Shorelines* tool does not currently include a SLR time-step in 2070. The sea level elevation in 2070 was emulated using the NOAA intermediate SLR scenario in 2100. This value (1.1 m) falls within NOAA's range of uncertainty (i.e., between the 17th and 83rd quartile) about the median projection of the high scenario in 2070 (i.e., 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. The detailed methodology of how inundation is modeled in *Future Shorelines* is given by Juhasz et al. (2023). 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). Furthermore, the presence of extensive tidal wetlands and seagrass beds in the IRL indicate prevailing wave and current processes do not contribute to widespread modification (e.g., erosion, deposition) of the basin’s geomorphology on times scales of years to decades. The exception to this generalization are areas located proximal to tidal inlets, but these represent <1% of the study area. Hence, no substantial changes to the basin’s bathymetry or topography are expected over the duration of time being considered in this investigation and therefore the assumptions of the bathtub model are not violated.

The seagrass data considered in this study (Seidel and Parkinson, 2014) were generated under two SLR scenarios: 0.6 m (2 ft) in 2050 and 1.2 m (4 ft) in 2100. The first scenario was used to model the effects of SLR on seagrass distribution in year 2050. The value of 0.6 m used by Seidel and Parkinson is greater than NOAA’s 2050 median high elevation, but it falls within the range of uncertainty for 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 was also considered a reasonable approach since the 1.2 m (4 ft) rise used in the original analysis falls within the range of uncertainty in the sea level elevation projected by NOAA in 2070 (Table 1).

As noted previously, the median high NOAA SLR trajectory is bounded by lower (i.e., 17th quartile) and higher (i.e., 83rd quartile) estimates that delimit the range of uncertainty in the elevation of sea level at each time step (Figure 6). These data also provide 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 high trajectory suggests that in 2050 sea level is expected to reach an elevation of 0.5 m relative to 2000 (Table 1). That value is bounded by a lower (0.3 m, 17th quartile) and higher (0.6 m, 83rd quartile) estimate that correspond to the range of likely sea level elevations for that year. Conversely, the lower and higher estimates can be used to determine the range (i.e., earlier, later) of possible 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 years. The uncertainty in the arrival times of the median estimate of sea level elevation in 2070 and 2100 were also calculated as +8/-7 years 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 years.

The NOAA trajectories include an estimate of *regional* VLM, which is an important component of relative SLR (Sweet et al., 2022). In the study domain, regional VLM is downward (subsidence) at a rate of 0.8 mm/y due to GIA (Knopp et al. 2014), 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 also 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 tall buildings or other large 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). 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

In this section, the results obtained from each county are combined and summarized for the entire study domain. County-specific tabular and graphical summaries of the results are provided in the supplemental material files as referenced therein.

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). By 2050 (Figure 7, Table 2), 77% (n=36) of the ramps are partially submerged, 21% (n = 6) are largely submerged and one ramp (2%) is completely submerged. Over the next 20 years (2070), the proportion of partially submerged ramps declines 13% (n = 6), while those largely to completely submerged increase to 26% (n = 12) and 62% (n = 29), respectively. By 2100, all ramps are either largely (4%, n = 2) or completely (96%, n = 45) submerged. There are notable differences between the six counties, as for example 100% (n = 10) of the ramps located in Volusia County will be submerged by 2070 while in the other counties that will not occur until 2100 or thereafter (Supplemental Figure 1).

Spoil islands

This study evaluated 76 IRLAP spoil islands that extend from southern Brevard County to the Ft. Pierce Inlet in St. Lucie County (Supplemental Table 3). By 2050 (Figure 7, Table 2;), 13% (n = 10) will be partially submerged, 32% (n = 24) largely submerged and 55% (n = 42) submerged. In 2070, 12% (n = 9) will be largely submerged and the proportion of completely submerged islands increases to 88% (n = 67). By the end of this century, 4% (n = 3) will be largely submerged and all others (96%, n = 73) completely submerged. In reference to the designated service of each island, by 2050 39% (n = 10) of the recreational islands and 80% (n = 32) of the conservation islands will be completely inundated. Over the next 20 years, the extent of submergence increases to 77% (n= 27) and 98% (n = 39), respectively. The single island designated as a critical wildlife area will be submerged by 2070. By the end of this century, only 3 (9%) of the recreational islands will be above sea level. All other islands will be under water (Supplemental Figure 2). Geographic distinctions of island vulnerability to SLR are not apparent by 2050 (Supplemental Figure 3) as about half are submerged in each county. However, by 2070 nearly all (88%, n = 67) are submerged except one each in Indian River and St. Lucie County and 7 in Brevard County. By the end of the century, the only islands that are not totally submerged are in Brevard County.

On-site treatment and disposal systems

There are 126,091 known or likely OSTDS located within the boundaries of the study domain (Supplemental Table 4). By 2050, 7% (n = 8,869) will be inundated and over the next 20 years, that number rises to 11% (n = 13,725). By the end of the century, 27,121 (22%) will be submerged (Figure 7, Table 2). Nearly half of these at each time-step are located in Brevard County (Supplemental Figure 4).

Wastewater treatment plants

The on-line search indicated there are eleven WWTP in the study domain (Figure 1, Supplemental Table 5). In 2050 (Figure 7, Table 2), the parcel on which one facility (9%) is located will be partially submerged. By 2070, one each (9%) will be partially or totally submerged and 18% (n = 2) largely submerged. In 2100, one each will be partially to largely submerged, while the proportion of WWTP parcels totally submerged increases to 55% (n = 6). Of the five counties, risk to inundation will be apparent by 2070 in all but Martin County, where the single plant will be above sea level to the end of this century (Supplemental Figure 5).

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). By 2050 (Figure 7, Table 2), seagrass coverage will be reduced to 66% (n = 19,075 ha) relative to the 2009 baseline. By 2070, seagrass coverage will be 95% (n = 27,263 ha) relative to the baseline condition. This expansion in coverage is largely attributed to the presence of large tracks of natural land in Brevard County (Supplemental Figure 6). There are no distribution data for the seagrass segments in year 2100, however a comparison between the MDL in each segment and the median elevation of sea level (Supplemental Figure 7, Supplemental Table 7) suggests a decrease in seagrass distribution will resume after 2070 as rising water levels deepen the basin, resulting in a reduction in area of the IRL substrate receiving sufficient light to sustain seagrass growth. By 2100, the lagoon water depths will exceed the MDL of all seagrass segments.

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 or proxy is compromised (Supplemental Figure 8). Mitigation options to restore loss of ecosystem services are also presented for consideration. Importantly, all five counties in which the study domain is nested participated in the development of the submergence simulation model *Future Shorelines* as project partners. The authors have sustained this collaboration through their continued participation in subsequent projects and proposals, the sharing of relevant publications and, most recently by seeking their consultation during the investigation described herein. This coproduction of scientific information ensured the mitigation strategies and outcomes as described below were realistic and actionable (Beier et al., 2017).

In Brevard County alone, the annual economic benefit of waterfront and marine industries and businesses in 2017 was over $325 million (Seidel et al., 2018). Without intervention, the ecosystem services provided by access to public motorized boat ramps will be substantially compromised under conditions of SLR and by 2070 only 13% will be functional. In addition to the loss of access, the economic benefits of waterfront and marine activities are also expected to decline commensurate with diminishing water quality, seagrass and the fisheries that depend upon a healthy estuary. Mitigating the loss of access could be accomplished by on-site renovations (e.g., ramp redesign, elevating the parking lot), however this is not a long-term 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. This challenge will be particularly acute at sites located along the barrier island shoreline (28%, n = 13), where ramp infrastructure elevations are typically <1 m above present sea level. Relocation would appear to be the only permanent remedy, but this option assumes land will be available in the future. This may be problematic given the current and predicted development trends in Central Florida (1000 Friends of Florida et al., 2017). Hence, plans to identify and purchase land should be initiated as early as is practical.

By 2050, only 13% of the spoil islands considered in this evaluation will be providing recreational, conservation, or critical wildlife services. The loss of both natural and dredge-spoil island ecosystem services to SLR extends well beyond the IRL. For example, the Florida Fish and Wildlife Commission has identified 29 islands as critical wildlife areas in coastal waterbodies that rim the state (Florida Fish and Wildlife Conservation Commission, 2025). These provide habitat for a variety of nesting, migratory, and wintering birds, including state-threatened species. All are at risk to inundation. 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 functioned as intended and even if they were, are not capable of keeping pace with SLR. So, their mitigative capacity is expected to decline over time. Fill placement is expensive and would likely be challenging to permit on all but the recreational islands. As an alternate, but equally expensive mitigation strategy, existing habitat restoration and management activities for some islands could be rescoped as future mitigation sites for seagrass recruitment. This could be accomplished by recontouring the topography, removal of exotics, and native plantings as was demonstrated in southern St. Lucie County (Clark, 2013).

Seven percent (n = 8,869) of the known or likely OSTDS parcels considered in this study will be partially to completely below sea level by 2050 and over the next 20 years an additional 4,856 parcels are inundated. But the impact on estuarine ecosystem function caused by OSTDS inundation and the release of nutrient pollution (e.g., impairment of water quality, eutrophication, HAB) will begin well before submergence of the parcels on which they have been constructed because OSTDS are installed below ground level. Sea level rise is projected to increase by one foot (0.3 m) over the next 25 years (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. 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. Similar performance risks to OSTDS and wastewater collection systems caused by SLR have been described throughout the southeastern US coastal zone (Cooper et al., 2016; Flood and Cahoon, 2011) and worldwide (Gyimah et al., 2024). It was beyond project scope to quantify the cumulative effects of the combined release of wastewater nutrient pollution from OSTDS and WWTP on estuarine water quality, clarity, and related ecosystem services. However, given the fact that wastewater-derived nutrient concentrations are currently promoting eutrophication, HABs, and catastrophic seagrass loss (c.f., Herren et al., 2021), rapid intensification of declining ecosystem health is expected in tandem with SLR.

In recognition of risks to ecological services posed by OSTDS, a 2023 Florida state law (HB1379) now requires property owners with septic systems to convert them to sewer or to an enhanced nutrient-reducing septic tank by July 1, 2030, if they live adjacent to waterbodies that do not meet water quality standards (Florida State Senate, 2023). This includes the IRL. Compliance is already challenging because it requires municipalities to invest in the upscaling of existing services to accommodate a surge of new consumers and a hefty (~$10 - 25k) financial investment by individual homeowners. A host of grant and loan options are being considered to reduce this financial burden (e.g., Martin County’s Connect to Protect). In Brevard County, septic to sewer conversions are being prioritized to both accommodate the availability of financial resources and target high pollutant loading areas using models like ArcNLET and STUMOD. However, the output of these models is based upon existing conditions (e.g., distance to waterbody, elevation) and assumptions (e.g., at least 2' of separation between the drain field and the water table) which are subject to change as sea level rises. The OSTDS output of this project provides a complementary set of observations to consider during the formulation and updating of mitigation strategies and conversion project prioritizations.

To mitigate the environmental impacts of WWTP inundation, upgrades were recently completed to the South Beaches facility located in Brevard County (Figure 1, Site e). Risks posed by SLR prompted the decommissioning and relocation of two treatment facilities originally constructed on the IRL (i.e., Vero Beach Sewer Plan, Ft. Pierce WWTP; Figure 1, Sites h and i). It is critical that this effort continue at an accelerating pace, although it is a lengthy process and expensive. For example, the duration of time from concept to completion of the Ft. Pierce WWTP was ~25 years and construction costs were ~$150 million. Furthermore, the vulnerability of Vero Beach and Ft. Pierce plants was intuitive given both are located along the IRL shoreline. The site-specific submergence simulations generated during this investigation have been shared with municipal resilience officers and public works personnel (c.f., Parkinson et al., 2025). This science-based information can be considered during the periodic (e.g., intra-annual) review and revision of long-term (typically ~20 years) capital improvement plans that otherwise are typically based upon the design life of facility components, duration of use, or a change in regulatory policy.

Seagrass meadows are predicted to contract by about one-third over the next 25 years due to the shrinking seabed area above segment MDLs. 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). By 2070, the distribution of seagrass expands to 95% of the baseline value. This is substantially driven by the overtopping of natural areas located on Brevard County (e.g., 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. After 2070, SLR will continue to deepen the IRL basin and by end of the century, water depths will exceed all seagrass segment MDLs. This suggests that the horizontal accommodation space created by shoreline transgression onto natural areas will become the primary driver of seagrass resilience over the latter half of this century.

The loss of seagrass habitat translates into a substantial reduction in ecosystem services, including nursery habitat for fisheries, food for numerous marine organisms, shoreline protection, ecotourism, and carbon sequestration, which combined are valued at \$19,000 ha^{-1} per year (Costanza et al., 1997). Given the projected decline of IRL seagrass habitat in 2050 will be roughly 9,700 ha, this equates to an annual economic loss of \$185 million. Projects constructed to improve water clarity and quality (e.g., septic to sewer conversions, living shorelines, stormwater diversion or treatment) must remain a high priority, as seagrass recovery and resilience to SLR is tightly coupled with the availability of light and nutrient loading (Medina et al., 2022; Morris et al., 2021; Steward and Green, 2007; Van Katwijk et al., 2024). The emerging science of seagrass transplanting offers a novel restoration option (c.f., Renton et al., 2011), although to date these have been largely unsuccessful (Main et al., 2024). This investigation has produced a dataset that quantifies meadow resilience to SLR in each of the seagrass segments. This information can be used as an additional tool during the search for potential transplant locations that are hospitable for seagrass growth and long-term success. Future gains in seagrass coverage are also possible on undeveloped parcels that surround the basin, hence protection and acquisition of natural lands throughout the watershed should be a long-term management strategy. To ensure a successful transition onto these areas, resource practitioners may have to modify their existing comprehensive conservation management plans and strategies to *accept* changes that they may have been *resisting* in the past in order to maintain a landscape and related ecosystems services that are becoming ever more incongruent with the physical environment in which they exist (c.f., Schuurman et al., 2020).

The output of *Future Shorelines* is based upon locally derived data (e.g., regional sea level trends, local VDatum water level transformations, and parcel-specific information). However, the methodological approach developed in this investigation has broad applicability to other regions where estuarine ecosystem services have historically degraded because of land use changes and that are now subject to the additional stress of SLR. For example, practitioners can utilize publicly available SLR projection and visualization tools (e.g., Climate Central, 2021; NOAA, 2024b, 2021) to simulate submergence at a resolution sufficient to conduct an environmental risk assessment. When combined with other geospatial information (e.g., location maps of recreational facilities, wetlands, OSTDS, WWTP), the risks of inundation can be quantified as a function of sea level elevation or time step. This knowledge can then be used to develop an adaptive management plan that is temporally and spatially tuned to specific *emergent* ecosystem services. The methodology can also be applied to assess risks to *submerged* resources (e.g., seagrass, oyster reef) under conditions of SLR, although this requires access to additional geospatial (e.g., habitat maps, bathymetry) and environmental (e.g., sensitivity to changes in water depth or clarity) data that may not be readily available.

The submergence simulation output and ecosystem service outcomes of this study are based upon several assumptions (i.e., no changes in geomorphology or natural land use within the watershed, constant MDL). (1) As noted previously, changes in the bathymetry or topography over the duration of time being considered in this analysis are unlikely because the processes that are largely responsible for the IRL's geomorphology operate over centuries to millennia. (2) Changes in the distribution of existing natural lands are unlikely given they are typically held in the public trust for the purpose of conservation in perpetuity. (3) Changes in seagrass distribution reported in this study are based upon a 2009 baseline and since then coverage has persistently declined (Morris et al., 2022) as a result of decreasing water clarity and quality. Hence, the simulations may overestimate the coverage (ha) at each time step.

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 is at present unknown but 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 IRL ecosystem services using the on-line geospatial tool *Future Shorelines*. Sea level rise was modeled using NOAA's median high scenario-based 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 widespread and substantial degradation in ecosystem services as early as 2050. The submergence tool does 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. Mitigation options to reduce risk are discussed for each of the five ecosystem services or their proxies. These include (1) sustain access to boat ramps by periodically performing targeted on-site construction upgrades such as elevating the parking lot and access roads, (2) re-align spoil island management plans to allow some sites to be modified to function as future mitigation sites for seagrass recruitment, (3) integrate submergence simulations into OSTDS and (4) WWTP environmental risk assessments to identify high-priority locations and establish capital improvement priorities, and (5) incorporate modeled spatial-temporal trends in future seagrass distribution into the site selection process of transplanting experiments to enhance the probability of seagrass growth and long-term success.

The development of the submergence simulation tool and discussion of mitigation options benefited by collaboration with project partners responsible for resource management in the study domain. This coproduction ensured the simulation outputs and mitigation options were realistic and actionable. The risks to estuarine ecosystem services induced by urbanization and sea level rise are reported worldwide and the methodological approach of this study offers a novel means of developing or enhancing mitigation strategies.

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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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Author Response to Reviewer Comments

We appreciate the comments of both the Chief Editor and Review #1 and provide the following responses.

Chief Editor

1. Fig.1 refers to "miles" which is not an acceptable unit in a scientific paper, please convert to metric scale.
   Author response. Updated figure to express distance in kilometers.
2. Overall, the paper has still too many display items. I think that you should move at least four of them to the online supplement, in order to keep the paper in a readable format.
   Author response. Reduced the number of figures from 10 to 7 by moving 3 to online supplement.

Reviewer #1:

I thank the authors for their response to the previous comments. I think that the manuscript has been greatly improved. However, there are two remaining confusing issues from my perspective:

1. I am unable to link the sea level projections used in Table 1 and the figure 6 with the NOAA SLR scenarios https://urldefense.com/v3/__https://coast.noaa.gov/slr/*/layer/sce/0/-9011351.96817323/3305872.3714223434/8/satellite/81/0.8/2050/high/midAccretion__;Iw!!FjuHKAHQs5udqho!PNt7P3kq9vbj3hpgASluI11JUgQZvwEyfjjlJuGPzsZBfzlbZkniwb8RzUYdwIAcIsVPMnCts4ZF4gJZ$ -specifically I think that the projections presented in the paper are significantly higher than those of NASA (?).

   Author response. The sea level rise projections we utilized were obtained from NOAA's online Interagency Sea Level Rise Scenario Tool at https://sealevel.nasa.gov/task-force-scenario-tool. We initially reference the source of our data on page 5. We did not use the SLR Viewer you reference above. More specifically, we utilized the data for the Trident Pier at Port Canaveral as stated in the text. That data can be downloaded from the Interagency SLR website, which we did as follows:

psmsl_id	process	Units	scenario	quantile	2050	2070	2100
2123	total	mm	High	17	338.6864	737.6864	1813.686
2123	total	mm	High	50	461.6864	980.6864	2094.686
2123	total	mm	High	83	613.6864	1171.686	2317.686

   So, the data in Table 1 and Figure 6 of our manuscript were generated from this download are not significantly higher than that of NOAA or NASA (hence the term Interagency).
2. I also suggest using the international unit system (not feets) in order to avoid confusion, or at least adding the units in the table (not only in the legend)
   Author response. International units of measure are used in Table 1. US Customary are provided in parentheses because some of the early work we reference was conducted in feet. This is indicated in our caption.
3. the justification of using the bathtub model is essentially based on the assumption that there is no dynamic response of the indian river lagoon to sea level rise and other interventions. Obvioulsy I have no expertise on this particular case but this is quite difficult to believe that there will be no change in sedimentation rates, in vegetation impacts on sedimentation as sea level rise. I would argue that a careful statement explaining that this first approximation is

intended to provide a first order evaluation of the extent of the problem would be more convincing.

Author response. It is challenging to envision how changes in the rate of sedimentation, either inorganic or organic (vegetation) could alter our submergence simulations of boat ramps, septic systems, or wastewater treatment plants since these are built components of the study domain. The manuscript includes a discussion of the "dynamic" (i.e., sediment erosion) response of the spoil islands to SLR and the outcomes of our simulations incorporate those processes (c.f. line 150 – 160). As we noted in the text (line 168 – 174), the presence of seagrass is an indication of the absence of "dynamic" processes (i.e., sediment erosion and deposition) that might otherwise locally violate the assumptions of the bathtub model.

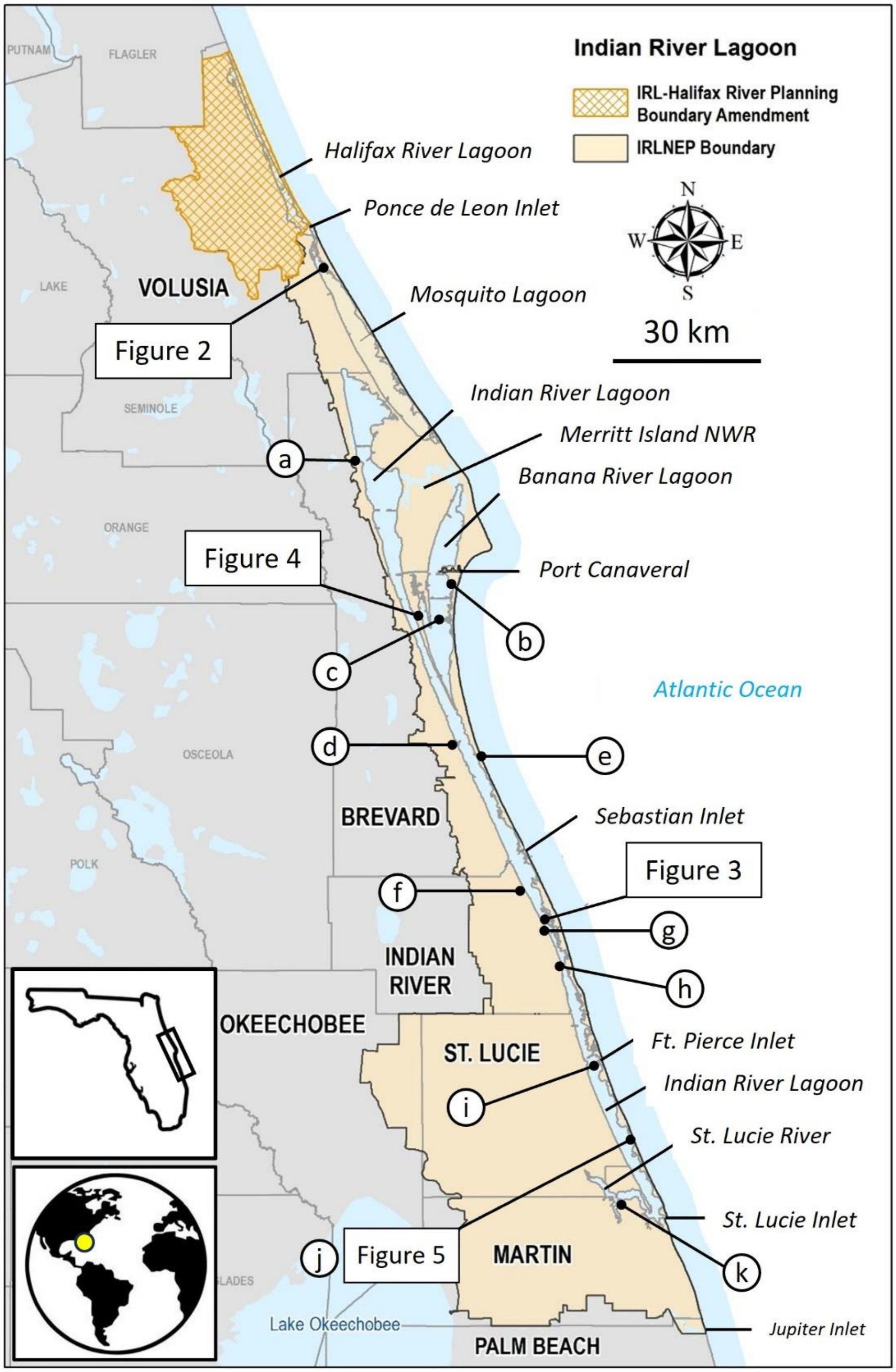

Figure 1. Regional location map of the study area. Circled letters indicate the location of wastewater treatment plants considered in this study. Geospatial data for all ecosystem services evaluated in this analysis can be found at https://doi.org/10.34703/gzx1-9v95/QYDD8Y. NWR = National Wildlife Refuge. Modified from Adams et al. (2024).

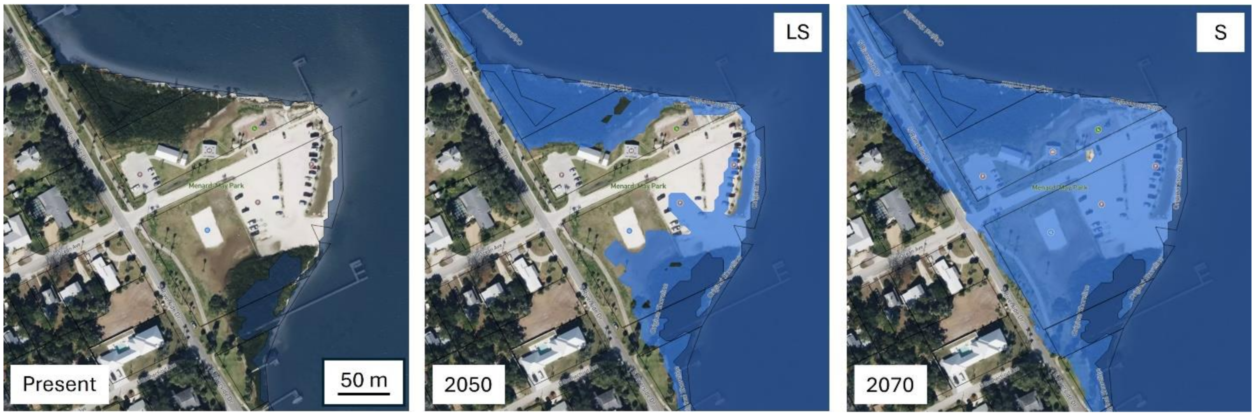

Figure 2. Submergence simulation of Menard May Park boat ramp, Volusia County. Left panel is present condition. By 2050 (center panel) the boat ramp will be largely submerged (LS) and in 2070 (right panel) the ramp will be completely submerged (S). See Figure 1 for location.

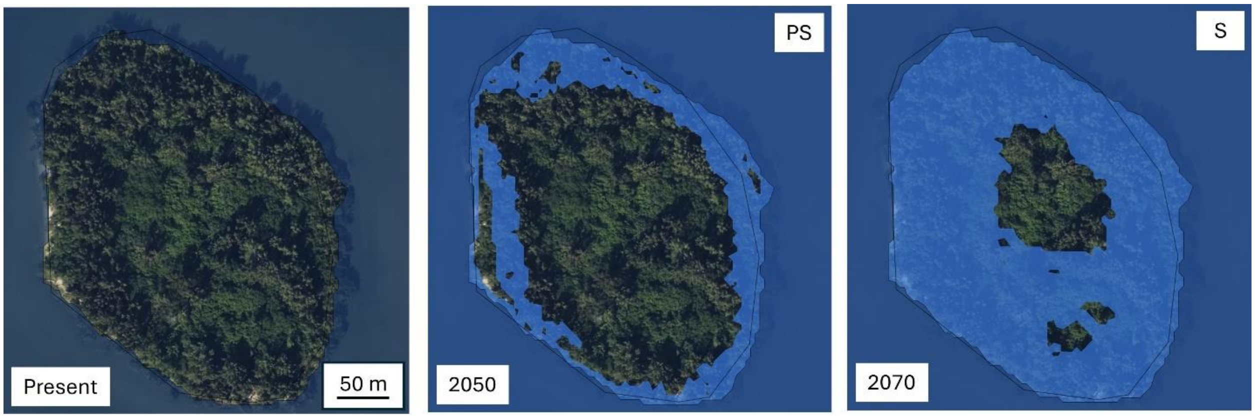

Figure 3. Submergence simulation of conservation spoil island IR35, Indian River County. Left panel is present condition. By 2050 (center panel) the island will be partially submerged (PS). Right panel is 2070 and indicates a portion of the island will remain emergent at that time. However, the island 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.

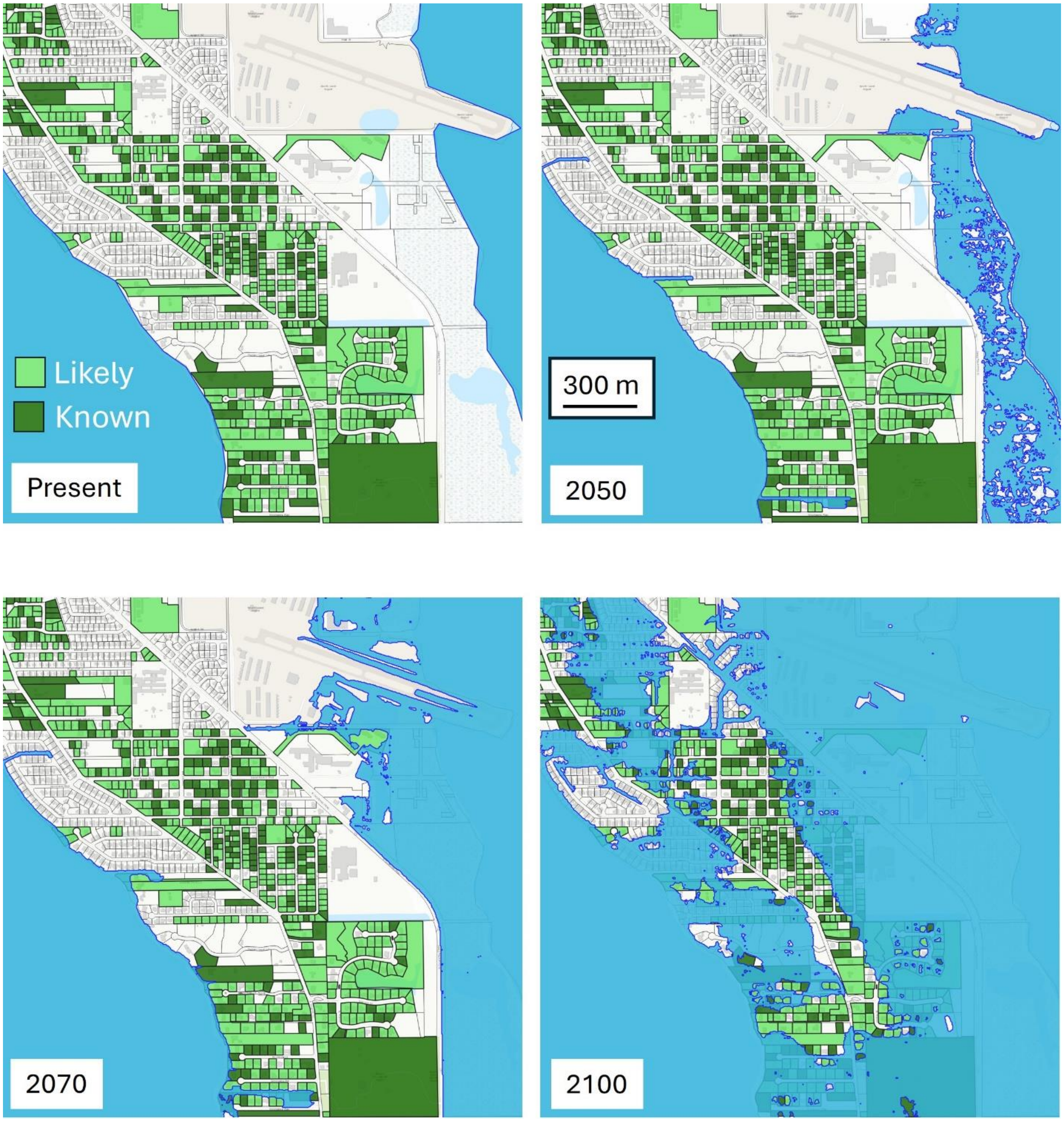

Figure 4. Submergence simulation of Merritt Island OSTDS (septic), Brevard County. Colored polygons indicate location of parcels in which the presence of an OSTDS has been confirmed (i.e., known) or is likely. Top left is present condition. In 2050 (top right), the eastern shoreline will experience some 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.

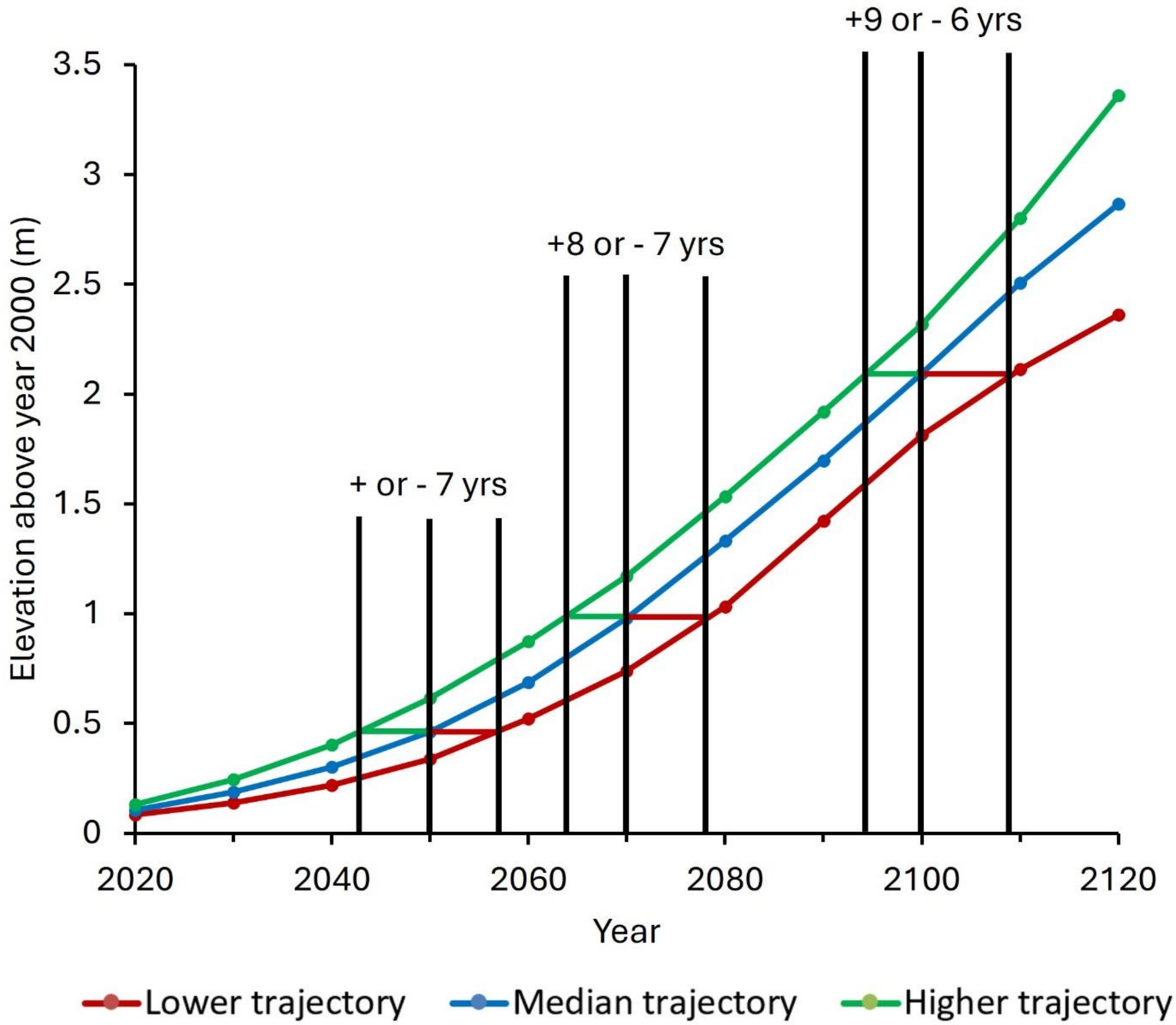

Figure 6. NOAA sea level rise trajectories for the high scenario (NOAA, 2024a). At each of the 3-time steps considered, extrapolations of the median elevation (see Table 1) to its intersection with the lower and higher trajectories yield the arrival time uncertainty for the target year (e.g., + or – 7 yrs).

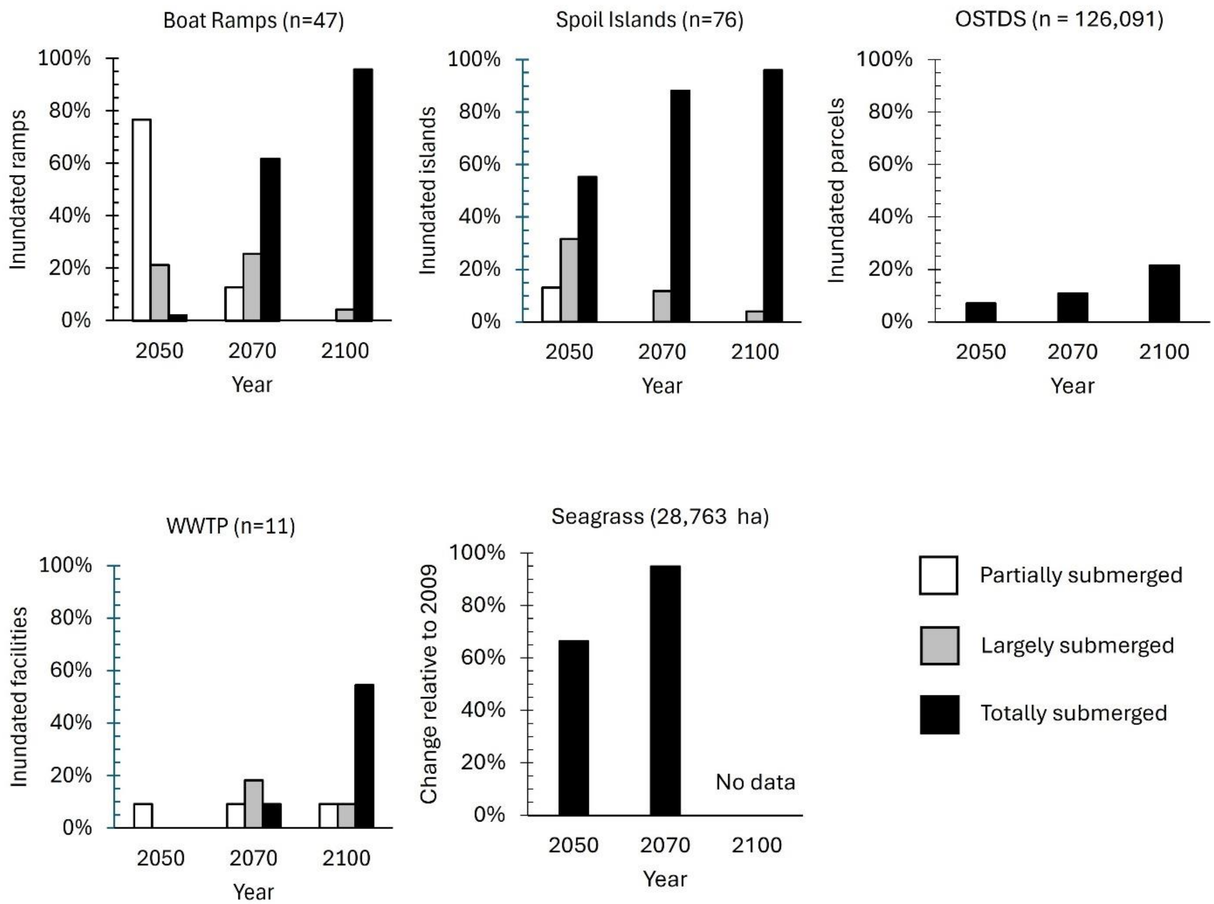

Figure 7. Submergence simulation results for each of the five ecosystem service attributes considered in this study. For all but seagrass, loss of site function is expected once largely submerged. See Table 2 for the data used to generate this summary.

Table 1. Top. Observed rate of sea level rise (mm yr^{-1}) trends for the study area as recorded at the NOAA Trident Pier station, Port Canaveral, Florida. Error expressed as uncertainty. Middle. Range of sea level elevations in meters (ft) corresponding to lower (17th quartile), median, and higher (83rd quartile) trajectories at 10-year time steps to year 2100. Uncertainty in arrival time of sea level elevation in target years 2050, 2070, and 2100 relative to the median values are also shown (see Figure 6 for graphical depiction of data). Positive and negative values indicate elevation arrives later or earlier than median value, respectively. Data are NOAA scenario-based trajectories relative to year 2000 at the Trident Pier station (NOAA , 2024a). Bottom: Sea level elevation in meters (ft) used in this investigation to simulate submergence. The *Future Shorelines* on-line geospatial tool does not consider year 2070. Therefore, the median NOAA intermediate SLR elevation at year 2100 was used since it falls within the likely range of high-scenario values 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

	Year									
Trajectory	2040	2050	Uncertainty	2060	2070	Uncertainty	2080	2090	2100	Uncertainty
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)	1.8 (6.0)	+6 yrs
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)	2.1 (6.9)	na
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)	2.3 (7.6)	-9 yrs

	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)	

Table 2. Summary of submergence simulations at each of the three time-steps organized by the ecosystem service attribute and location (county). Simulations expressed as percent of total number or acreage (seagrass) of attribute impacted by sea level rise and binned into three outcomes as defined in text: PS = partially submerged, LS = largely submerged, and S = submerged. Raw data provided in Supplemental Tables and Figures.

			2050			2070			2100		
Attribute	County	n	PS	LS	S	PS	LS	S	PS	LS	S
Boat Ramp	Volusia	10	70%	30%	0%	0%	0%	100%	0%	0%	100%
	Brevard	13	69%	31%	0%	23%	15%	62%	0%	0%	100%
	Indian River	8	75%	13%	13%	13%	13%	75%	0%	13%	88%
	St. Lucie	8	75%	25%	0%	0%	50%	50%	0%	0%	100%
	Martin	8	100%	0%	0%	25%	63%	13%	0%	13%	88%
	Total	47	77%	21%	2%	13%	26%	62%	0%	4%	96%
Spoil Island	Volusia	ND	-	-	-	-	-	-	-	-	-
	Brevard	16	38%	19%	44%	0%	44%	56%	0%	19%	81%
	Indian River	38	8%	34%	58%	0%	3%	97%	0%	0%	100%
	St. Lucie	22	5%	36%	59%	0%	5%	95%	0%	0%	100%
	Martin	ND	-	-	-	-	-	-	-	-	-
	Total	76	13%	32%	55%	0%	12%	88%	0%	4%	96%
OSTDS	Volusia	17988	-	-	21%	-	-	28%	-	-	34%
	Brevard	25966	-	-	33%	-	-	58%	-	-	45%
	Indian River	29229	-	-	30%	-	-	47%	-	-	7%
	St. Lucie	35995	-	-	47%	-	-	62%	-	-	11%
	Martin	16913	-	-	37%	-	-	55%	-	-	22%
	Total	126091	-	-	33%	-	-	51%	-	-	22%
WWTP	Volusia	ND	-	-	-	-	-	-	-	-	-
	Brevard	5	0%	0%	0%	0%	20%	20%	20%	20%	60%
	Indian River	3	0%	0%	0%	33%	0%	0%	0%	0%	33%
	St. Lucie	2	0%	0%	0%	0%	50%	0%	0%	0%	100%
	Martin	1	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Total	11	9%	0%	0%	9%	18%	9%	9%	9%	55%

Seagrass (ha)	Volusia	4203	-	-	59%	-	-	43%	-	-	ND
	Brevard	22231	-	-	66%	-	-	107%	-	-	ND
	Indian River	2330	-	-	85%	-	-	68%	-	-	ND
	St. Lucie	ND	-	-	-	-	-	-	-	-	-
	Martin	ND	-	-	-	-	-	-	-	-	-
	Total	28763	-	-	66%	-	-	95%	-	-	-

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