Research Article

Relevance of ongoing mitigation efforts to reduce Indian River Lagoon water quality impairment and restore ecosystem function under conditions of a changing climate

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Abstract The Indian River Lagoon National Estuary Program has determined the principal factors that have historically degraded water quality and ecosystem function can be mitigated by nine adaption actions focused on reducing nutrient pollution from surface- and storm-water runoff, on-site sewage treatment systems and waste-water treatment plants. If properly sited and designed, the resiliency of these projects under conditions of climate change will be enhanced, as will the probability they will perform as intended throughout their design life. Analysis of the predominate remediation strategies currently pursued within the IRL watershed suggests their environmental contribution and duration of performance is proportional location, scale, and cost.

Introduction

Climate change has globally impacted atmospheric temperatures, inducing regionally significant changes in historical patterns of snowfall, rainfall, and river flow. More extreme climate events—like heavy rainstorms and record-high temperatures—are already taking place (National Academies of Sciences, Engineering, and Medicine 2016). Estuaries are especially sensitive to these changes because they are located at the land-sea interface and therefore attributes of water quality, habitat value, and ecosystem function are largely determined by what inputs to the basin from the adjacent terrestrial and marine environments. As the climate changes, so too will both of these environments, which will ultimately compromise an estuary's resiliency as upland rainfall and river flow patterns change, air and water temperature rises, the intensity and frequency of tropical storm and hurricane landfall increases, sea-level rises, and pH declines (Gillanders et al. 2011; Statham 2012; James et al. 2013; Robins et al. 2016; Gregg, Reynier, and Hilberg 2017). The resilience of an estuary under conditions of a changing climate may be further stressed if the system is currently impaired by the effects of coastal urbanization and concomitant water quality degradation due to elevated pollutant (e.g., sediment, nitrogen, phosphorous) loadings (Lotze et al. 2006; Sherwood 2016; Robins et al. 2016; Lefcheck et al. 2018).

The Indian River Lagoon (IRL) includes 27% of Florida's eastern coastal wetlands and is home to more species than any other estuary in North America, including some 4,300 plant and animal species (St. Johns River Water Management District 2007). To facilitate the protection and restoration of its water quality and ecological integrity, the IRL was recognized by the Environmental Protection

Agency as an Estuary of National Significance in 1990. Thereafter, research designed to enhance the knowledgebase from which to formulate and implement a Comprehensive Conservation and Management Plan (CCMP) quickly expanded. What followed was growing evidence that the ecological and biological integrity of the lagoon had degraded over the past 50 years due to a decline in water quality caused by: (1) pollution from point and nonpoint sources, (2) disruption in the natural patterns of water circulation in the lagoon, and (3) alterations in freshwater inflows, especially during wet season discharges (Sigua et al., 2000). The current IRL CCMP (Indian River Lagoon National Estuary Program 2019) was designed to reduce water quality impairment caused by historical urbanization within the watershed. It did not specifically address future conditions (e.g., climate change) that may exert additional stress on the system. This was by design, as the IRL National Estuary Program (NEP) had already committed to becoming a Climate Ready Estuary by adopting the recommendations of a forthcoming risk analysis of the conservation and management challenges arising as a consequence of climate change (Indian River Lagoon National Estuary Program 2021). This paper reports on the results of that effort and then evaluates the relevance of ongoing mitigation efforts to reduce water quality impairment under conditions of a changing climate.

Study Location

The IRL (Figure 1) covers an area of 353 km^2 and is composed of three distinct and connected estuaries: the Indian River, Banana River, and Mosquito Lagoon. It is present along 156 miles of coastline and encompasses almost 40% of Florida's east coast. Its 2,284 km^2 watershed sprawls over five counties and spans two climate zones: temperate, and tropical. An additional two counties (Okeechobee, Palm Beach) were integrated into the natural watershed upon the construction of surface water storage and conveyance infrastructure in the early part of the 20^{th} Century. Thirty-eight incorporated cities and approximately 1.6 million residents live within the boundaries of the IRLNEP. The lagoon's total economic contribution to the region is estimated to be about ten billion dollars generated by five IRL-related industry groups; living resources, marine industries, recreation and visitor, resource management, and defense & aerospace. marine industries, tourism (East Central Florida Regional Planning Council and Treasure Coast Regional Planning Council 2016).

Data Sources

Adaptation Action Plan. The Indian River Lagoon Climate Change Adaptation Plan was completed in 2020. (Indian River Lagoon National Estuary Program 2021). The results and recommendations were based upon a three-year investigation that was conducted in two parts:

- Part 1. Vulnerability Assessment: (1) risk identification, (2) risk analysis, (3) risk prioritization

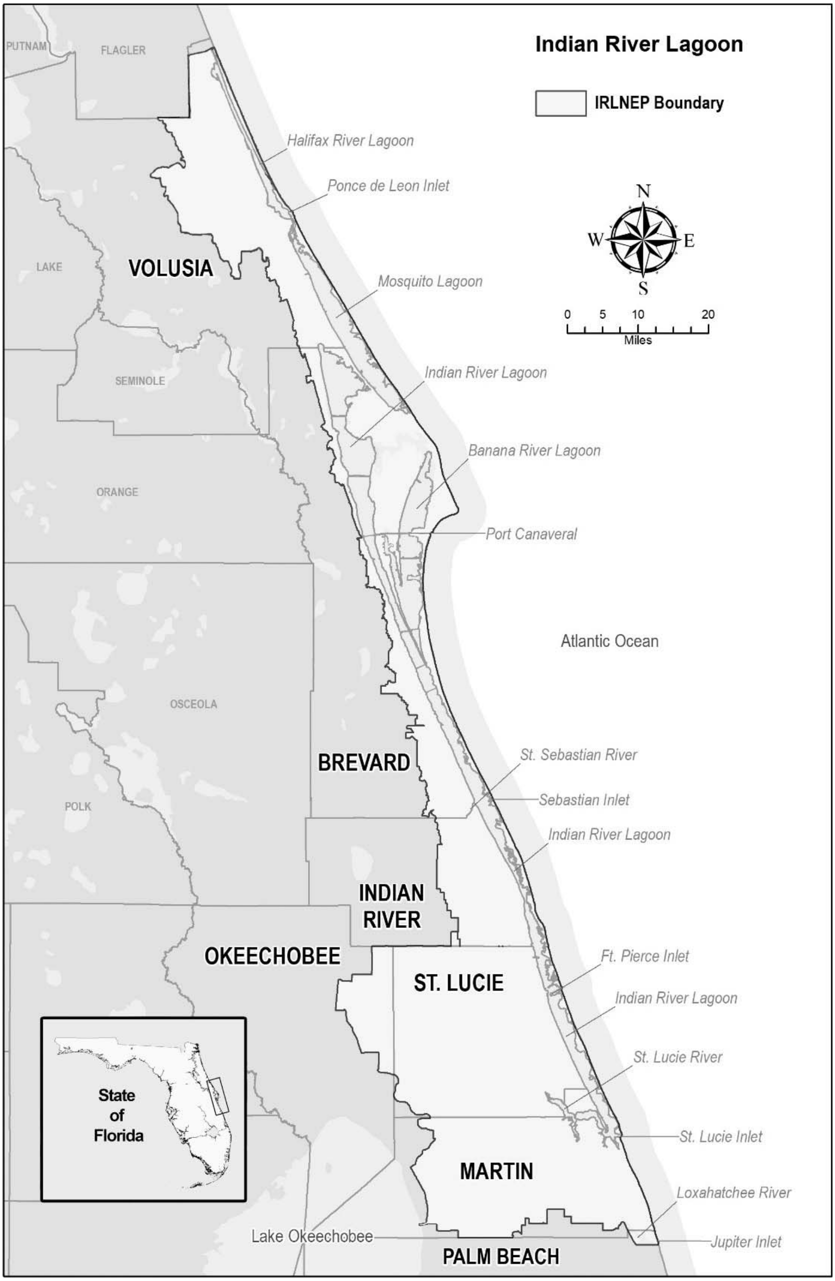

Figure 1. Regional location map of study area.

Figure 2. Indian River Lagoon Natoinal Estuary Program Comprehensive Conservation and Management Plan Vital Signs Wheel.

- Part 2. Adaptation Action Planning: (1) formulation of adaptation actions, and (2) preparation of action plans

The vulnerability assessment was based upon analysis of the components of the IRL CCMP "vital signs wheel" (Figure 2). The wheel consists of three missions (e.g., One Lagoon), five categories (formally goals, e.g., Water Quality), and 32 vital signs (e.g., Impaired Waters) central to the success of the program. The vital signs were created as critical indices to measure progress in each category. Associated with each vital sign is one or more action plan formulated to promote specific activities to facilitate category progress. The components of the vital sign wheel were evaluated regarding the potential for climate change to compromise the program's mission specific to each of the five categories and 32 vital signs. Because climate change stressors could result in more than one risk to a particular vital sign or impact multiple vital signs, the number of climate-related risks was much greater

Table 1. Results of risk analysis to Indian River Lagoon National Estuary Program goals to climate change stressors.

	Stressor						Level of Risk				
Category and Vital Sign	Temp	PPt	Storms	pH	SLR	Sum	Accept	Highest	Higher	High	Sum
Water Quality											
Impaired waters	5	54	57	0	55	**171**	5	162	4	0	**166**
Wastewater	1	10	10	1	10	**32**	2	30		0	**30**
Stormwater and surface water	5	8	8	1	9	**31**	3	24	2	2	**28**
Hydrology and hydrodynamics	3	3	0	0	3	**9**	0	3	6	0	**9**
Legacy loads and healthy sediments	0	0	1	0	0	**1**	0	0	1	0	**1**
Atmospheric deposition	1	1	1	0	0	**3**	3	0	0	0	**0**
Sum	15	76	77	2	77	**247**	13	219	13	2	**234**
Habitats											
Seagrass	6	16	15	1	14	**52**	5	47	0	0	**47**
Living shorelines	1	1	2	1	2	**7**	3	0	4	0	**4**
Wetlands and impounded/ altered marshes	3	1	0	0	2	**6**	5	1	0	0	**1**
Sum	10	18	17	2	18	**65**	13	48	4	0	**52**
Living Resources											
Biodiversity	3	16	11	1	17	**48**	5	33	10	0	**43**
Species of concern	10	15	18	1	19	**63**	4	47	12	0	**59**
Invasive species	2	15	14	0	14	**45**	3	14	28	0	**42**
Commercial and recreational fisheries	3	15	19	1	14	**52**	4	42	6	0	**48**
Sum	15	45	51	2	47	**160**	11	103	46	0	**149**
Grand Total	**40**	**139**	**145**	**6**	**142**	**472**	**37**	**370**	**63**	**2**	**435**

than the number of vital signs being stressed. An action plan was then constructed by identifying a limited number of practical measures that could be undertaken to reduce the largest number of risks. The results and recommendations of the entire 3-yr effort were regularly vetted by members of the Indian River Lagoon Management Conference, all of whom are practitioners in the fields of science, policy, and resource management, as well as other watershed stakeholders directly contacted by the project team.

A total of 472 risks to the IRL CCMP were identified. Of those, fifty percent were associated with three vital signs: Impaired Waters, Wastewater, and Surface Water. Ninety-seven percent of these risks were induced by three climate change stressors: change in precipitation, increasing storminess, and sea-level rise (Table 1). Therefore, the formulation of adaptation action plans focused on these three vital signs and climate stressors. A total of nine action plans are proposed to reduce risks to the IRL CCMP caused by climate change (Table 2). A detailed description of the methods employed to generate these action plans can be found in Parkinson et al. (2021a; 2021b).

Mitigation Projects. There are a broad variety of mitigation strategies and related projects that have been implemented over the past few years throughout the IRL watershed to improve water quality and ecosystem function. These include: (1)

Table 2. Adaptation Actions proposed to reduce risks to the IRL CCMP (Indian River Lagoon National Estuary Program, 2019) caused by climate change. WWTP = wastewater treatment plant, OSTDS = on site treatment and disposal system, SWSC = surface water storage and conveyance infrastructure.

Stressor	Adaptation Action
Changes in precipitation	Reduce pollutant loadings from WWTP during high rainfall events
	Reduce pollutant loadings from OSTDS during high rainfall events
	Reduce pollutant loadings from SWSC during high rainfall events
Increasing storminess	Reduce pollutant loadings from WWTP due to more frequent and intense storms
	Reduce pollutant loadings from OSTDS due to more frequent and intense storms
	Reduce pollutant loadings from SWSC due to more frequent and intense storms
Sea-level rise	Reduce pollutant loadings from WWTP caused by rising water table and sea level (inundation, erosion)
	Reduce pollutant loadings from OSTDS caused by rising water table and sea level (inundation, erosion)
	Reduce pollutant loadings from SWSC caused by rising water table and sea level (inundation, erosion)

nature-based, soft, or green (e.g., living shorelines, seagrass planting, oyster reefs), (2) legacy load reduction (e.g., muck removal), (3) surface- and storm-water improvements (e.g., retention - detention ponds, wetland restoration, baffle boxes), (4) septic system upgrades (e.g., connection to municipal services), and (5) waste water treatment plant (WWTP) improvements (e.g., denitrification trenches, upgrades to water reclamation and treatment). To date, several billion dollars have been invested by local, regional, state, and federal entities towards the completion of these mitigation projects. A complete list, updated annually, is available on the Indian River Lagoon National Estuary Program website under the heading "Annual Reports" and summarized in Figure 3 and Table 3. Cursory inspection of these data indicates nature-based projects have been a persistent mitigation strategy over the past six years, while the number and scale (e.g., small <\$250,000, large >\$250,000) of the more complicated and costly surface water, septic, and WWTP upgrades have steadily increased; a logical outcome of the maturation of local, regional, and state agency efforts with time.

Discussion

To provide context with which to evaluate the contribution of ongoing mitigation efforts towards reducing impairment of IRL water quality, a cost to benefit matrix was created that also considers a performance timeline and risk assessment to climate change (Figure 4). These are grouped into three categories, each of which is described in the following sections.

Nature-Based. The construction of nature-based mitigation projects is a very popular strategy that targets nutrient pollutant and/or turbidity loads by increasing biological uptake (Herbert et al. 2018; Beck et al. 2017) and shoreline stability using benthic filter feeders and native vegetation. These projects are also a very

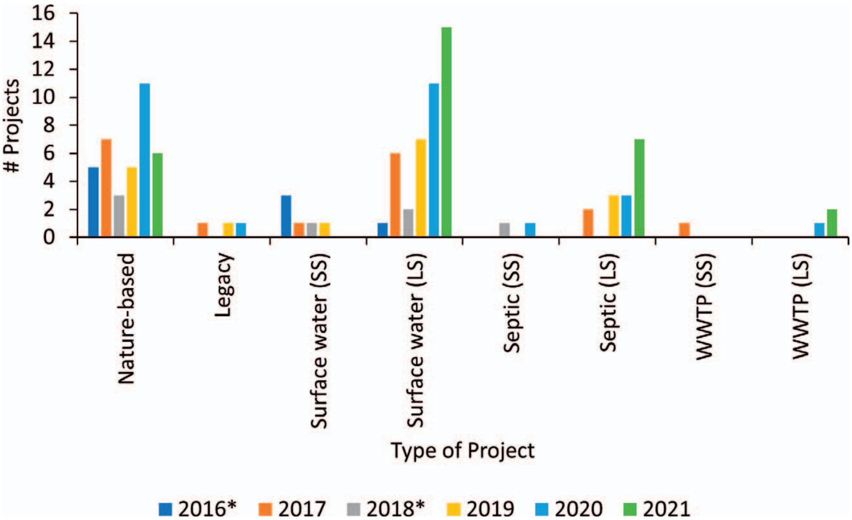

Figure 3. Mitgation projects undertaken in the Indian River Lagoon watershed since 2016. Surface water includes storm water. Asterisk indicates data only from projects funded by the National Estuary Program. Otherwise, the data include other local (e.g., municipalilies, counties), regional (e.g., South Florida Water Management Disitrct), and state (e.g., Florida Department of Environmental Protection) agencies. SS = small scale (<\$250K). LS = large scale (>\$250k). Data derived from Indian River Lagoon National Estuary Program Annual Reports.

successful platform to elevate public awareness through active participation in their construction. They are relatively inexpensive (e.g., living shorelines are about \$100 per linear foot) and can generally be completed within one year. However, they are relatively small in scale (e.g., typically no more than a few hundred feet) and it is not currently known how long it will take the installations to perform at the level of ecosystem services (e.g., reduction of N and P; Onorevole et al. 2018; Carlozo

Table 3. Mitigation projects undertaken in the Indian River Lagoon watershed since 2016. Surface water includes storm water. Asterisk indicates data only from projects funded by the National Estuary Program. Otherwise, the data include other local (e.g., municipalilies, counties), regional (e.g., South Florida Water Management Disitrct), and state (e.g., Florida Department of Environmental Protection) agencies. SS = small scale (<\$250K). LS = large scale (>\$250k). Data derived from Indian River Lagoon National Estuary Program Annual Reports.

	2016*	2017	2018*	2019	2020	2021	N
Outreach	6	5	1	3	1	1	17
Nature-based	5	7	3	5	11	6	37
Legacy	0	1	0	1	1	0	3
Surface water (SS)	3	1	1	1	0	0	6
Surface water (LS)	1	6	2	7	11	15	42
Septic (SS)	0	0	1	0	1	0	2
Septic (LS)	0	2	0	3	3	7	15
WWTP (SS)	0	1	0	0	0	0	1
WWTP (LS)	0	0	0	0	1	2	3

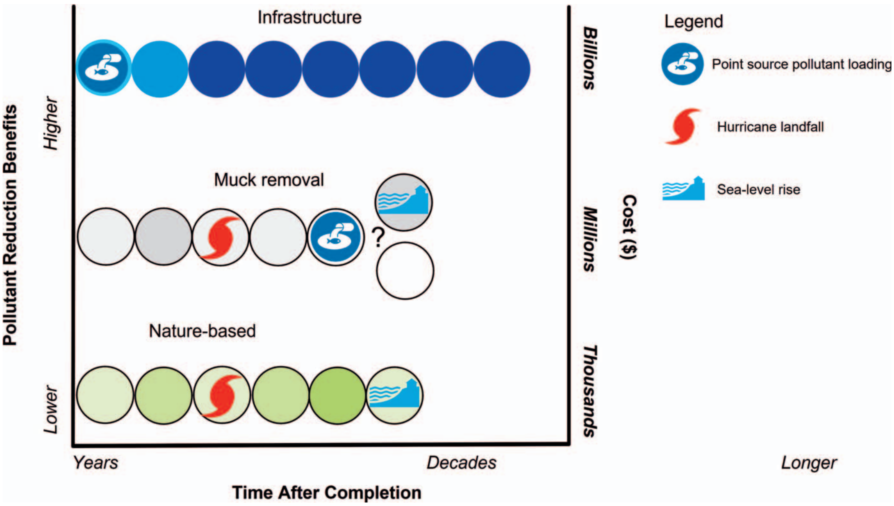

Figure 4. Relevance of ongoing mitigation efforts with respect to duration of performance, cost, and pollution reduction benefits. Color intensity proportional to performance.

2014) for which they are purported to provide. Nature-based installations, and especially living shorelines, are also vulnerable to physical damage by an elevated wave climate associated with storm events. Their resiliency under conditions of accelerating sea-level rise is a present unknown. Specifically, whether their components can keep pace with an expanding vertical and horizontal accommodation space (assuming the latter is present).

Legacy Pollutant Loads. Removal of fine-grained, organic-rich sediments (e.g., muck) has been an integral part of restoring the IRL because these deposits have been shown to increase turbidity, consume oxygen, smother benthic habitat and is a source of dissolved nitrogen (N) and phosphorus (P) that diffuses into the overlying water of the lagoon (Fox and Trefry 2018). Muck dredging has been undertaken at several locations in the IRL (e.g., Turkey Creek, Eau Gallie River, Cocoa Beach) and other projects are planned. However, there are several challenges to dredging efficiency that have yet to be overcome including incomplete removal within the targeted basin or along the margins where seawalls, docks and other marine structures are present. Secondly, there is a lot of muck and dredging is expensive. An estimated 6,000,000 yd^3 of muck have accumulated in the IRL over the past 70 years (Fox et al. 2017) and projects completed to date (e.g., Cocoa Beach, Eau Gallie River) have cost about \$50 yd^3 (St. Johns River Water Management District 2020; 2019). For example, the Eau Gallie River project removed about 200,000 yd^{-3} of muck at a cost of \$7,300,000. Locating and managing disposal sites and dewatering effluent are also a challenge.

Muck is also is easily resuspended and redistributed into areas not previously contaminated during the passage of tropical storms and hurricanes (c.f., Fox and Trefry 2018). Perhaps more important is that fact that the accumulation of muck

Table 4. Sampling of threats to the mission of other National Estuary Programs located along the United States west coast, Gulf of Mexico, and east coast.

Location	Nutrients	Surface / Storm Water	Septic Systems	WWTP	Climate Change	Source
Puget Sound, WA	x	x	x	x	x	Puget Sound Partnership 2018
San Francisco Bay, CA	x	x	x	x	x	San Francisco Estuary Partnership 2022
Coastal Bend Bays & Estuaries, TX	x	x	x	x	x	Coastal Bend Bays & Estuaries Program 2020
Tampa Bay Estuary Program, FL	x	x	x	x	x	Tampa Bay Estuary Program 2017
Delaware Estuary, DE	x	x	x	x	x	Partnership for the Delaware Estuary 2017

persists because the conditions of formation have not yet been abated (Trefry and Trocine 2011). That said, the continued rise in sea level may, over time, reduce the frequency and extent to which muck deposits are subjected to remobilization and redistribution during storm events.

Infrastructure. The number and scale of infrastructure projects (e.g., surface/ storm water conveyance and storage systems, septic system upgrades, WWTP improvements) designed to reduce the flux of pollutants into the Indian River Lagoon have increased over the past few years (Figure 3). Initially, these were predominantly small-scale projects (e.g., <$250,000; City of Edgewater stormwater improvements, City of Satellite Beach bioretention ponds) that were 'shovel ready'. Large-scale projects have come on line more recently (e.g., Ocean Breeze septic upgrades, C-44 stormwater treatment area, North Sebastian) at a cost of millions. A commitment of billions of dollars will be required to fund projects currently in the planning, design, or land acquisition phase. These will take years to decades to complete. However, if designed properly (e.g., long-term environmental changes caused by sea-level rise and saltwater intrusion are considered during site selection and/or design) these projects will perform their intended function throughout the duration of their design life (50+ years).

What comes next?

It will take time to restore the IRL and require a multi-faceted approach as is currently being pursued. Nature-based and muck dredging projects are an important component of the restoration matrix. However, until the *sources* of pollution that have compromised water quality and ecosystem function are substantially reduced or eliminated, restoration success will likely remain elusive. This will require the construction of many, very large infrastructure projects, some of which have already been completed and many more in queue. In all cases, it is clear the legacy of any and all projects will be in large part dependent upon their resiliency to climate change. A project designed and constructed without consideration of the effects of changing precipitation patterns, increasing storminess, and sea-level rise will have a shorter functional life span and are more likely than not to falter in their performance or even fail before the design life is reached.

Restoring and sustaining water quality and ecosystem function under conditions of increasing urbanization, aging infrastructure and climate change are a common challenge to every coastal resource agency responsible for the management of our estuaries and bays (c.f., Table 4). A successful outcome will require a sustained campaign of public education and outreach, the formation of effective partnerships with local, regional, state, and national entities, and the commitment of billions of dollars over generations. This is a daunting task, but substantial progress has already been achieved as a consequence of these efforts, providing evidence a successful outcome is within our reach.

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