COASTAL SYSTEM VARIABILITY OF THE BEACH-NEARSHORE ENVIRONMENT FROM NATURAL AND ANTHROPOGENIC INFLUENCES

By

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ABSTRACT

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The coastal system provides habitat, storm protection, and economic value. In particular, Florida’s beaches are subject to chronic coastal erosion resulting from natural and anthropogenic influences. The most common mitigation response is the nature-based solution of beach nourishment. While this method is widely considered effective, quantifying changes from the dredge and placement on the physical environment is critical to ensure best management practices. The first step in addressing the need to identify gaps in knowledge relating to natural and human-induced changes to the continental shelf, a comprehensive literature review of the US East and Gulf coast continental shelves was conducted identifying needs for more expansive sand searches, a greater understanding of storm impacts on shelf morphodynamics, planning for long-term use of offshore sediment sources, and the impact of dredging on habitats. This study then evaluated the northern Palm Beach County beaches adjacent to the Jupiter Inlet over multiple years to understand the effects of natural and human influence on the morphology and sedimentology of the beach-nearshore environment. Beach sediment was coarser near the Inlet and finer downdrift (south). Seasonal changes in the nearshore from storms decreased the grain size and eroded beaches, whereas nourishment increased grain size and expanded beach width. Influences of physical characteristics of the beach-nearshore environment on the ecosystem were examined based on two important marine species: loggerhead sea turtles and blacktip sharks. No adverse impacts from restoration activities were found on loggerhead reproductive success. However, the active 2020 hurricane season resulted in lower reproductive success metrics. The blacktip shark migration coincides with the typical nourishment construction window. High turbidity in the nearshore was documented in association with multiple nourishment events during the two-year study. The blacktip sharks were quantified in the nearshore south of the nourishment; however, whether the turbidity was influencing the shark aggregates or habitat preference remains unknown. These results support numerous benefits of beach nourishment but suggest further research is needed to evaluate how project construction may impact nearshore fauna. The findings of this study are important for coastal managers who may consider reviewing best management practices of the beach-nearshore system.

COASTAL SYSTEM VARIABILITY OF THE BEACH-NEARSHORE ENVIRONMENT FROM NATURAL AND ANTHROPOGENIC INFLUENCES

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LIST OF ABBREVIATIONS

BOEM	Bureau of Energy Management
BUDM	Beneficial Use Dredge Material
FDEP	Florida Department of Environmental Protection
GIS	Geographic Information System
GPS	Global Positioning System
MHW	Mean High Water
NAVD88	North American Vertical Datum 1988
PBC	Palm Beach County
R-##	Coastal Range Monument Number
RTK	Real-Time Kinematic
USCRP	United States Coastal Research Program
USA	United States of America

CHAPTER 1: INTRODUCTION

Coastal Systems and Their Importance

The coastal system varies in width and scope depending on location as it includes any part of the land that is influenced by some marine conditions and extends seaward to the continental slope (Davis and FitzGerald, 2009; Masselink and Gehrels, 2014). Barrier island systems are a coastal environment within the coastal system that are formed due to the combined action of wind, waves, and longshore currents (Davis and FitzGerald, 2009; Masselink and Gehrels, 2014). Barrier island systems are a composite of sub-environments that include beaches, dunes, the nearshore, tidal inlets, and back-barrier which consists of estuaries, lagoons, tidal flats, and salt marshes (Davis and FitzGerald, 2009; Masselink and Gehrels, 2014). Certain interactions between sub-environments such as the beach and nearshore environments are especially important to understand due to the large impacts of the inherent geology along with external forces such as winds, waves, and currents (Wright and Thom, 1977; Masselink and Gehrels, 2014). The physical properties of these sub-environments such as the beach and nearshore and important to understand due to their effect on coastal ecosystems (Masselink and Gehrels, 2014).

Beaches provide many benefits including recreation, habitat, economy, and protection from storms, but are subject to chronic erosion from natural and anthropogenic causes. In response to erosion, beach nourishment is a common practice to increase the resilience of the beach. Sediment used in beach nourishment is frequently obtained from offshore borrow areas and the process of removing sediment and placing it on the beach can disturb the nearshore which is also important due to its large role in the Florida state and national blue economy, habitat, and recreation. Therefore, understanding the physical changes and impacts on the environment and habitats is needed to ensure long-term sustainability and best management practices. The primary goal of this dissertation is to better understand the impacts of natural and anthropogenic influences on morphology and sediment variability of the beach and nearshore environment.

The coastal zone is a fragile environment and small changes in its physical processes can have profound impacts (Masselink & Gehrels, 2014). Coastal erosion on beaches is caused by natural and anthropogenic influences. Natural influences that can cause erosion are largely a result of seasonal storm events that increase the magnitude of physical processes and drivers of change including waves, currents, and tides (Leatherman et al, 1994; Masselink & Gehrels, 2014). Anthropogenic causes for beach erosion are commonly associated with hard structures such as jetties, breakwaters, groins, and other infrastructure that alter the wavefield through diffraction and refraction, ultimately changing the shoreline and the beach in the vicinity of the structure (Komar and McDougal, 1988; Hanson and Kraus, 2001).

In Florida, 87% of the coastline is considered “critically eroded” (FDEP, 2016). Estimates of 80-85% of Florida’s beach erosion can be attributed to inlets (Dean, 1991). However, tidal inlets are crucial to barrier island systems as 30-60% of sediment deposited within the system is transported through the inlet (Hayes, 1980). The inlets also often function as sediment sinks that can be used to nourish the downdrift side that frequently erodes (Work and Dean, 1995; Dean 1996; Galgano, 2007). Tidal inlets, especially when structured with jetties, have large impacts on beach morphology and sediment transport due to strong ebb- and flood-currents, the ability to disrupt normal littoral sediment transport, and complex alterations of the wave fields due to interactions with the ebb-tidal delta (Work and Dean, 1995; Dean 1996; Galgano, 2007; Elko et al., 2020). Beach and barrier island morphodynamics must include sub-environments and processes of tidal inlets that lead to complex and wide-reaching morphologic impacts.

A common nature-based solution (Bridges et al., 2013; Bridges et al., 2015a; Bridges et al., 2015b) to beach erosion is nourishment (or soft stabilization) where a large amount of beach-compatible sediment from offshore on the continental shelf, inlet, or upland sources, is added to the beach system advancing it seaward (Dean, 2002). Since 1920, there have been more than 650 beach nourishment projects that have placed greater than 325 million cubic yards of sediment in the US (Elko et al., 2021; National Beach Nourishment Database, 2021). Since 1921, the volume of sediment placed per decade has increased at an exponential rate (Elko et al., 2021). Beach nourishment is often the preferred stabilization technique as it provides habitat, protection from storms, and increases space for recreational activities, all while protecting the beach (National Research Council, 1995). In northern Palm Beach County, it has been noted that a future without nourishment projects would result directly in coastal erosion, loss of habitat, and recreational opportunities, and indirectly result in damages to the local economy (USACE, 2017). On both varying spatial and temporal scales, the influence of beach nourishment on the coastal system has been studied extensively, often with varying results depending on the location and oceanographic and geologic conditions (Dixon and Pilkey 1991; Davison et al., 1992; Kana and Stevens, 1992; Browder and Dean, 2000;

Finkl and Walker, 2002; Nordstrom, 2005; Kana, 2012; Roberts and Wang, 2012; Benedet at al., 2013). However, few studies have focused on dredging-induced variability associated with obtaining borrow sediments from offshore.

Sediment source in beach nourishment is important due to the quality of sediment as well as the cost (purchase, transport, and placement). Sediment most frequently is either sourced from inlets, upland mines, or the continental shelf and should be compatible with the native sediment (Houston, 2017). However, sediment properties can vary between common borrow sources (Dean, 2002). Inlet sediment is often placed on beaches as “beneficial use of dredged material” (BUDM) as inlet sediments can consist of more poorly sorted sediments with larger grains (i.e., thalweg) resisting advection (Wang and Beck, 2012; Brown and Briggs, 2020). Upland mines often can have a smaller mean grain size and better sorting than typical beach sediment due to the dominance of terrestrial or paleo-processes compared to the high-energy coastal processes (OAI and CPE, 2012). More than 95% of all sand volume placed in shoreline protection projects is sourced through offshore dredging (Dean, 2002) which places a large importance on understanding the continental shelf and sediment characteristics and distribution along with the dynamics on the shelf. Continental shelf sources generally are reworked shelf sediment and sand ridges from previous sea levels which are most suitable for beach placement (Finkl et al., 2005; Finkl and Khalil, 2005). The sediment on the continental shelf is a valuable resource that has been studied in certain capacities such as sediment characteristics and distribution for borrow areas, however, a comprehensive analysis of continental shelf sediment distribution, characteristics, and processes under normal, storm, and dredge conditions would greatly add to the knowledge of the resource.

It has been well documented that beach nourishment impacts the habitat through changes in the sediment and morphology of both the beach and nearshore (Mortimer, 1990 and 1995; Andrew, 1995; Milton et al., 1997; Wood and Bjorndal, 2000; Rumbold et al., 2001; Dellert et al., 2014; Pike et al., 2015; Bladow, 2017). For threatened and endangered nesting sea turtles in Palm Beach County, nourishment increases nesting area (USACE, 2017), but changes to sediment and morphology on the beach after a nourishment project can impact nesting success (Ernest, 2001; Rumbold et al., 2001; Brock et al., 2009) and have implications for the ecosystem services of beaches (Bascom, 1951; Wiegel, 1964; Dingler and Reiss, 2002). Steep beaches can be more challenging for nesting turtles to climb (Wood and Bjorndal, 2000; Turkozan et al., 2011) and sediment characteristic variability can also cause digging issues when turtles attempt to nest (Mortimer, 1990 and1995).

Blacktip sharks are an ecologically important mesopredator that migrates to South Florida’s nearshore waters in the winter and are known to frequently aggregate in shallow water directly offshore in areas such as the Jupiter Inlet (Castro, 2010; Kajiura & Tellman, 2016). Although found throughout the nearshore region, there are numerous unknowns about the aggregation patterns including if their aggregations are influenced by specific bathymetric features or how they may respond to natural or anthropogenic caused turbidity. It is possible that during dredge or storm activity, changes to the continental shelf may impact the aggregation patterns of these sharks (Hays et al., 2016) through bathymetric changes or due to water quality concerns.

Dissertation Significance and Research Objectives

The main goal of this dissertation research is to improve the understanding of the coastal system morphodynamics, from the beach to the outer continental shelf, and sediment changes resulting from natural and anthropogenic processes that could impact ecosystem services. To achieve this goal, this dissertation is organized as five separate projects detailed in chapters 2-6 with each project addressing a specific objective. In project 1, a comprehensive literature review of the current state of understanding of the US continental shelf sediment distribution and dynamics under normal, storm, and dredge conditions was compiled to identify gaps in knowledge. In project 2, sedimentology and morphology of the beaches in northern PBC were examined to establish a baseline of beach and sediment distribution and characteristics. In project 3, morphologic and sedimentologic changes to the beach-nearshore system were quantified in response to dredge and placement in two consecutive years, including the impact of high-energy wave events. Project 4 evaluated the environmental influences of sediment and morphology on loggerhead sea turtle nesting, hatching, and emergence success. Project 5 evaluated the impacts of multiple beach nourishment projects on nearshore water quality and habitat of the migratory blacktip shark. The outcomes of this dissertation will provide significant contributions to coastal system science integrating across the fields of morphodynamics, water quality, ecology, and habitat conservation. These results aim to aid improvements to best management practices in coastal restoration and conservation efforts.

CHAPTER 2: DISTRIBUTION AND DYNAMICS OF US CONTINENTAL SHELF SEDIMENT AND MORPHOLOGY: A BRIEF REVIEW OF THE PRESENT STATE OF KNOWLEDGE

Introduction

The continental shelf is a quasi-defined, geographical location found along coasts globally serving as an important sediment resource that provides habitat and economic benefit. Domestically, the continental shelf refers to all submerged land, its subsoil, and seabed that are seaward of the United States (US) and is referred to as lands beneath navigable waters (43 U.S. Code § 1301). In the US there are four primary continental shelf regions: Gulf of Mexico, Atlantic, Pacific, and Alaska continental shelf (Figure 1; BOEM 2020). This brief summary focuses on the shelf dynamics along the US Atlantic and Gulf of Mexico continental shelves.

Figure 2.1 Map of US continental shelf regions (Office of Natural Resource Revenue [ONRR], 2021).

The tectonic classification of the Atlantic coast is Amero-trailing edge and the Gulf is a Marginal sea coast. Both coasts are located on passive margins far from tectonic plate boundaries (therefore minimal geologic activity) and have wider continental shelves than the tectonically active Pacific and Alaskan coasts (Inman and Nordstrom 1971; Davis and FitzGerald 2009). The US Atlantic coast shelf has an average depth of 55-70 m and width ranging from ~2 km in Palm Beach County, FL to ~120 km offshore Savannah, GA (Atkinson et al. 1983). The continental shelf is a gently sloping (approximately 1°) platform that terminates at the continental slope at a typically agreed-upon maximum water depth of 150 m (Davis and FitzGerald 2009; Pinet 2019). The continental shelf area is often subdivided by researchers into the inner continental shelf and outer continental shelf (infrequently a mid-continental shelf is included within the outer) based on specific geomorphology (Figure 2). The commonly agreed-upon depth for the inner shelf is either <20 m or the approximate depth of closure (Kourafalou et al., 1996; Dalrymple and Hoogendoorn, 1997; Williams et al., 2012; Nnafie et al., 2014). The inner shelf tends to have shallow waters with higher wave energy and coarser sediment accumulation, whereas the outer shelf is typically classified as a low-energy environment that allows for finer sediment deposition (Figueiredo et al. 2016; Pinet 2019). The inner and middle shelf designations contain most modern sedimentary deposits with relict deposits on the outer shelf (Dame 1990; Kulp et al. 2001; Figueiredo et al. 2016; Pinet 2019).

The US continental shelf is highly valued as a resource for energy and as a source for restoration quality sediment. Comprehensive geotechnical and geophysical investigations of continental shelf sediment include information on the distribution of restoration quality sediment, hydrographic structures in the area, analysis for available volume, and proximity to the placement location. Geotechnical investigations frequently consist of jet probes and vibracores to search for and collect *in situ* sediment samples to be analyzed for sediment characteristics. Geophysical investigations can include seismic reflection profiling, side-scan sonar, magnetometer, and bathymetric data (Finkl and Khalil, 2005). Project specific compatibility is based on grain size distribution and composition of the site that is being restored (i.e., borrow sediment closely matching the native sediment), but specific policies vary by state. For beaches, in New Jersey, grain size distribution of the potential source must be greater than 90% sand (grain size >0.0625 mm) for dry beach placement (State of New Jersey 2021). Florida and North Carolina both require that the placed beach sediment cannot contain more than 5% fine material, as defined as <0.062 mm (Koch et al. 2011; Richardson 2020).

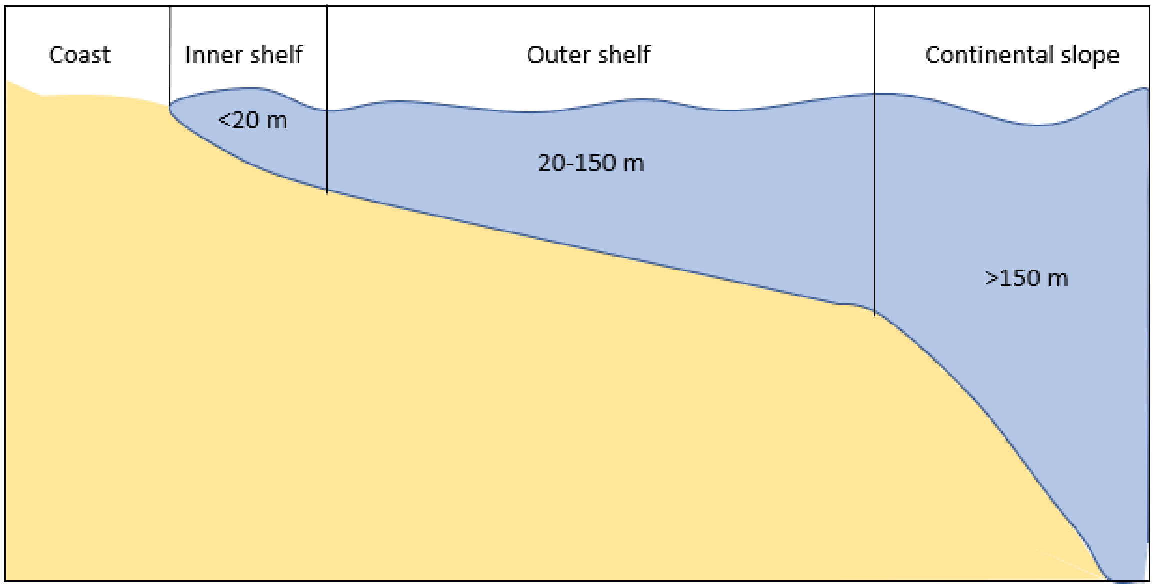

Figure 2.2 Vertically exaggerated profile view of continental shelf with inner and outer shelf outlined.

This study presents a brief comprehensive analysis of the various sources of information on continental shelf geomorphic variability to synthesize the current state of knowledge and identify gaps or additional research needs. The concise literature review presented focuses on the nature and distribution of sediment and morphology of the US Atlantic and Gulf coast continental shelves under normal conditions, storm conditions, and dredging conditions. Normal conditions are characterized as the typical state of morphology and sediment distribution in the absence of a large physical disturbance. Normal conditions are often a product of previous storm conditions, however, they are observed under equilibrium. Storm conditions are evaluated based on the potential impact on continental shelf sediment and morphology altering the distribution or characteristics of borrow areas (locations identified or hypothesized to contain restoration quality sediment). Storm conditions also include post-storm event when the continental shelf is not in equilibrium. Lastly, dredge or sediment removal conditions are based on sediment removal and placement processes as morphodynamics are directly altered through this process. By identifying gaps in the current state of knowledge, we aim to inform research needs and contribute to best management practices that balance limited continental shelf resources and increasing coastal restoration needs.

Results

Normal Conditions

Multiple large-scale investigations and smaller case studies have yielded an abundance of information on the normal morphodynamics of the US continental shelf (Uchupi 1968; Swift and Field 1981; Figueiredo et al. 1981; Stubblefield et al. 1984; Trowbridge 1995; Goff et al. 1999; Snedden and Dalrymple 1999; Brooks et al. 2003;

Edwards et al 2003; Locker 2003; Finkl et al. 2007; Khalil et al. 2018; Steele et al 2019). Sediment distribution is mapped frequently in gray literature, available from state and national databases such as the Florida Department of Environmental Protection's Regional Offshore Sand Source Inventory, the Louisiana Sand Resource Database, or the Bureau of Ocean and Energy Management's Marine Mineral Information System which contains the Resource Evaluation Studies database. These databases contain many mapped and permitted borrow areas along with many areas considered potential borrow areas which would require more sampling. Shelf morphology studies can be generally classified based on the objectives or foci areas as 1) regional-scale ridge morphology for broader characterization of the coastal morphodynamic system, external forces, and static conditions; and 2) local-scale studies to inform morphodynamic process-driven investigations and static conditions.

The US Atlantic shelf consists of widespread bedforms known as sand ridges from the nearshore to the shelf edge consisting of both shoreface-connected and detached ridges (McBride and Maslow 1991; Guillen et al. 2017; Duran et al. 2018). The best-described sand ridges morphology have been from wide (>75 km), storm dominated inner continental shelves, with the most heavily studied shelf regions of the Atlantic extending between New York and the Carolinas in the Atlantic and dominated by Texas, Louisiana, and Florida, in the Gulf. Comparably, narrow shelves (Southeast Florida) or shelves with limited sediment availability (West Central Florida) have received less investigation (Brooks et al. 2003; Edwards et al. 2003; Harrison et al. 2003; Finkl et al. 2005; Finkl and Warner 2005; Finkl and Andrews 2008). The ridges along sediment starved coasts or with narrower shelves are often separated by exposed hard bottom (Harrison et al. 2003;

Finkl et al. 2005; Finkl and Warner 2005; Finkl and Andrews 2008). Further investigation of these regions is critical given numerous uninvestigated borrow sources despite the need for beach renourishment (Steele et al. 2019).

Shoreface-connected ridges are developed on the inner shelf at water depths generally less than 15 m where sediment is abundant and inner shelf hydraulics can entrain sediment (Figure 3; Swift et al. 1978; McBride and Maslow 1991; Trowbridge 1995; Nnafie et al. 2014; Duran et al. 2018). Offshore sand ridges or shoreface-detached ridges occur most frequently in the middle and outer shelf, maintained by a combination of tides in tidal-dominated environments and steady longshore currents in both tidal- and non-tidal dominated environments (Swift et al. 1972; Goff et al. 1999; Simarro et al. 2015; Duran et al. 2018). Sand ridges on the Atlantic shelf are commonly storm-generated, flow oblique to the shoreline, and migrate several meters per year along the coast (Uchupi 1968; Swift and Field 1981; Figueiredo et al. 1981; Trowbridge 1995; Goff et al. 1999; Snedden and Dalrymple 1999; Finkl et al. 2007; Games and Gordon 2014; Nnafie et al. 2014; Dronkers 2016; Pendleton et al. 2017; Duran et al. 2018). With increasing water depth, ridges are dominantly asymmetrical, vary in vertical and horizontal scale, and tend to be thicker and more widely spaced (Stubblefield et al. 1984; Snedden and Dalrymple 1999; Finkl et al. 2007). Other features typical of sand ridges are medium to large 2D and 3D dunes, hummocky ripples, and current ripples (Swift 1985; Dalrymple and Hoogendoorn 1997; Snedden and Dalrymple 1999; Li and King 2007; Dronkers 2016). It has been noted that in sand ridges shallower than 50 m there often are active sand dunes on the flanks driving ridge migration (Goff et al. 1999), however, in deeper waters, there is no evidence of secondary bedforms even though there still is evidence of sediment transport (Goff et al. 2005).

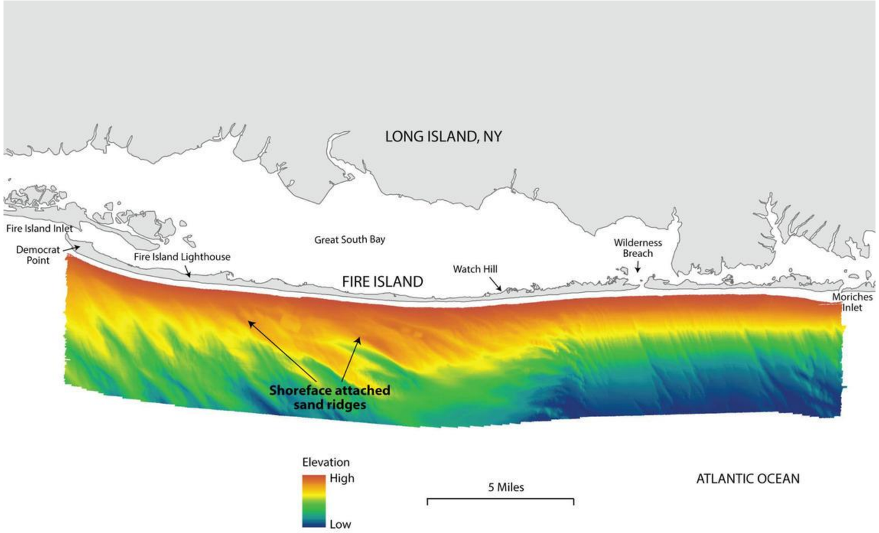

Figure 2.3 Bathymetric map of shoreface-attached ridges along the coast of Fire Island, US Atlantic Coast (USGS, 2011)

Migrating shelf sand ridges are frequently composed of mixed siliciclastic and carbonate sediment (Uchupi 1968; Dame 1990; Kulp et al. 2001; Brooks et al. 2003; Edwards et al. 2003; Harrison et al 2003; Locker et al 2003 Twitchell et al. 2003; Finkl et al. 2007; Nnafie et al. 2014; Khalil et al. 2018; Steele et al. 2019; Pinet 2019). The sediment located within the sand ridges varies between fine to coarse sand with coarser sediment on the stoss side than the lee side (Dalrymple and Hoogendoorn 1997; Snedden and Dalrymple 1999). However, grain size distribution varies cross-ridge and vertically (Snedden and Dalrymple 1999; Brooks et al. 2003; Finkl et al. 2007; Steele et al. 2019). In West Central Florida, sediment composition is primarily influenced by the source with local variability resulting from hydrodynamic processes (Brooks et al. 2003). Studies on continental shelf sediments have largely focused on the same geographic areas as the ridge morphology studies resulting in a gap of information in areas with narrow shelves or areas with limited sediment quantities (Finkl et al. 2005; Finkl and Warner 2005; Finkl and Andrews 2008; Duran et al. 2018).

Building on studies documenting strong, near-bottom, along-shelf currents during winter storms on the Mid Atlantic Bright (Beardsley and Butman 1974; Gadd et al. 1978) and fair-weather waves that were largely ineffective over the same mid-shelf ridges (McClennen 1973), Huthnance (1982) formulated a fluid-dynamic model explaining how oblique bottom currents bring about ridge growth when provided with a sufficient supply of sand. Huthnance (1982) considered tide-built ridges that exhibited flow-oblique orientation where crest lines of most linear banks were oriented counter-clockwise relative to peak tidal flow and the observed asymmetry of banks increased in proportion to the difference of ebb and flood tidal currents (Kenyon et al. 1981). Huthnance process for sand ridge formation requires four conditions: an initial irregularity most often on the inner shelf, ample sediment supply, currents capable of sediment transport, and time. The Huthnance processes have been widely applied to ridge construction and maintenance in both storm- and tide-dominated coastal settings (Swift 1985; Dalrymple and Hoogendoorn 1997; Snedden and Dalrymple 1999; Harrison et al. 2003; Reynaud and Dalrymple 2012; Duran et al. 2018; de Swart and Yuan 2019). It is important to note in the Huthnance process that the conditions indicate that ridges will form almost solely in transgressive settings (Swift et al. 1972; McBride and Moslow 1991; Snedden and Dalrymple 1999; Li and King 2007; Simarro et al. 2015; Duran et al. 2018).

Further process-driven investigations have found that sediment boundaries on the continental shelf have origins tied to subtle ridge morphology influenced by both paleo- and contemporary processes (Knebel 1981; Twitchell et al. 2003; Duran et al. 2018; de

Swart and Yuan 2019). Paleo-topography has a large influence on ridge development due to the alteration of hydrodynamics near various topographic features; however, once a ridge forms and migrates the evidence of the initial morphological influence is often erased (Snedden and Dalrymple 1999). While ridges can develop spontaneously (Trowbridge 1995), paleo-topographic features such as ebb-tidal delta deposits, nearshore bars, or irregularities of the ravinement surface can act as nuclei by disturbing linear flow for more rapid ridge development (Huthnance 1982; McBride and Moslow 1991; Snedden and Dalrymple 1999; Nnafie et al. 2014; Duran et al. 2018). The distribution of sediment resources within these ridges and hard-bottom habitats often reflects the reworking of previous deposits by changes in the inner-shelf hydraulic regime (Harrison et al. 2003; Locker et al. 2003; Twitchell et al. 2003; CSA 2009). Sediment transport rates can vary along different portions of submerged dune fields and certain hydrodynamics can alter sand ridges morphology (Snedden and Dalrymple 1999; Twitchell et al. 2003; Parsons et al. 2005; de Swart and Yuan 2019).

Sediment boundaries and sand ridge morphology along the continental shelf under normal conditions have been well-documented along the extensively studied regions of the Atlantic and Gulf (USACE, 2020). Further sediment sampling and modeling, especially within areas labeled unverified, can support the development of more predictable bathymetric maps at local and state levels beyond the previously identified potential and proven borrow areas. Shelf investigation challenges remain including the geographical extent size of ridges (up to tens of kilometers in length), temporal scale of change (years to thousands of years), and hydraulic variability from the numerous physical and sediment processes at various depths (Goff et al. 1999; van de Meene and van Rijn 2000; Goff et al. 2005; Li and King 2007; Pendleton et al. 2017; de Swart and Yuan 2019).

Storm Conditions

Storms present some of the most challenging conditions for research due to the difficulty in obtaining in situ measurements or observations during unfavorable conditions adding to the unpredictable nature of high-energy events. The US Gulf and Atlantic coasts experience frequent storm events including tropical storms and extratropical storms (e.g., cold fronts). Several small- and large-scale studies have been conducted on the shelf during or after large wave events with observations of sediment transport in shoreface-connected ridges (Figure 3), in shoreface-detached ridges, and between the shoreface and shelf (Swift 1985; Hoogendoorn and Dalrymple 1986; van de Meene et al. 1996; Li et al. 2004; Li and King 2007; Trembanis et al. 2013; Simarro et al. 2015; Games and Gordon 2014; Nnafie et al. 2014; Duran et al. 2018). Studies have also examined morphologic change and bedform migration along with ridge formation and alterations to the hydrodynamics (Niedoroda and Swift 1985; Hoogendoorn and Dalrymple 1986; Sumer 2002; Harrison et al. 2003; Trembanis et al. 2013; Nnafie et al. 2014). These investigations are important to determine if and how sediment and sand ridges and shoals in proven or potential borrow areas (locations that have had prior geophysical and technical investigation) or previously mapped areas may move due to storm-driven sediment transport. Small scale changes by storms occur when storms reach the critical threshold for sediment transport and larger-scale changes can occur when this threshold is achieved and maintained for extended periods of time (Niedoroda and Swift

1985; Hoogendoorn and Dalrymple 1986; Snedden and Dalrymple 1999; Nnafie et al. 2014).

Snedden and Dalrymple (1999) evaluated the extent of shelf sediment transport and found that most shoreface and shelf sand ridges are not declining, but rather are modified by waves, storm-, and tidal-currents which results in active accretion and migration across the shelf. Rates of accretion and migration vary widely and are driven by the magnitude, orientation, and period of waves and currents (Swift 1985; Snedden and Dalrymple 1999; Games and Gordon 2014). Information on storm impacts is often observed from asymmetrical ridges opposite normal flow (Snedden and Dalrymple 1999; Harrison et al. 2003; Trembanis et al. 2013) and there are possible links between storm waves and currents with shoal formation and maintenance. (Snedden and Dalrymple 1999; Simarro et al. 2015; Duran et al. 2018; de Swart and Yuan 2019).

Larger storms or wave events can move sediment and form large sand waves or ripples on the seabed between ridges in the troughs (Li and King 2007; Trembanis et al. 2013; Simarro et al. 2015; Duran et al. 2018). The longevity of seabed ripples and scours depend on the contemporary hydrodynamics at the location (Sumer 2002; Li and King 2007; Trembanis et al. 2013). Winter storms impacting the northern Atlantic shelf are often severe and create large wave ripples that sort sediment throughout the ridge fields that remain largely resistant to modification by normal conditions in the summer (Li et al. 2004; Li and King 2007). Similarly in West Central Florida, winter frontal passages impact the seabed resulting in frequent bedform activity leading to hard bottom exposure, ridge migration, and sorting of sediment (Brooks et al. 2003; Harrison et al. 2003; Twitchell et al. 2003).

While most sediment sources are disconnected from the shoreface, shoreface-connected ridges (Figure 3) are found to evolve primarily during intense storms with large waves and strong currents sustained for several hours to days multiple times a year resulting in significant sediment transport (Snedden and Dalrymple 1999; Nnafie et al. 2014). Migration of these shoreface connected ridges can impact nearshore morphology and navigational inlets. However, these ridges can also be crucial in the dissipation of wave energy (van de Meene et al. 1996; Nnafie et al. 2014; de Swart and Yuan 2019). Although shoreface-connected ridges are potential sand resources, borrowing from these ridges may not be beneficial due to the slower recovery time and potential reduction in wave dissipation benefits that could lead to beach erosion (Nnafie et al. 2014).

Storm-driven shelf morphodynamics can also have ecological impacts in the offshore region. Posey and Alphin (2002) examined the resilience and stability of an offshore benthic community in North Carolina in response to sediment borrowing and storm activities. They found that there was little evidence of acute change associated with the numerous storms that passed through the study area. Engle et al. (2008) investigated the impact of storms on benthic invertebrates after Hurricane Katrina and found that the benthic communities experienced local reductions in population, but no widespread ecological damage was noted after two months. Although numerous studies have analyzed ecological impacts of storms on benthic infauna, few have evaluated impacts on charismatic megafauna. For example, blacktip sharks migrate along the inner shelf in South Florida during the winter months where cold fronts are frequent (~6-10 days) (Brooks et al. 2003). The blacktips are known to aggregate in the nearshore around ebb-tidal deltas and sand bars (Kajiura and Tellman 2016), which are particularly active in response to storms. One of the key questions in the field of marine megafauna movement ecology is how much the physical environment influences animal movement and migration (Hays et al. 2014). Therefore, the need for additional studies such as the relationship between storm-induced morphology change and the distribution of shark aggregates, are widely recognized in conservation science.

Dredging Conditions

The shelf experiences significant local changes during dredging that alter the equilibrium of normal morphodynamics. When a potential borrow area is identified or hypothesized to exist based on geophysical or geotechnical, additional research is conducted to delineate boundaries containing sediment with the desired specifications (Finkl and Khalil, 2005). Large changes occur during and immediately after dredging of the shelf due to the removal of sediment and subsequent infilling of the dredge pit (location where sediment is removed from, resulting in a pit in the borrow area; Van Dolah et al. 1998; Jutte et al. 1999; Jutte and Van Dolah 2001; Greene 2002; Xu et al. 2014) and the morphodynamics both around the dredge pit and onshore (Figure 4; Kaufman and Pikley 1983; Dean and Dalrymple 1991; NRC 1995; Work et al. 2004; Benedet and List 2008; Hartog et al. 2008; Benedet and List 2009; Taiani et al. 2012; Benedet et al. 2013). Habitat is also most impacted at both the borrow and placement sites during the dredge and placement window (Andrew 1995; Jutte et al. 1999; Rumbold et al. 2001; USACE 2001; Greene 2002; Byrnes et al. 2004; Wilber et al. 2009; Dellert et al. 2014; Rosov et al. 2016; Wooldridge et al. 2016; Bladow 2017; Thompson et al. 2021). Infauna are removed from the seafloor and rebound times vary based on species and region (Greene 2002; Byrnes et al. 2004; Wilber et al. 2009; Rosov et al. 2016;

Woodridge et al. 2016). Finally, the water is most turbid during dredge-and-placement and can impact vagile species (Suedel et al. 2008; Wenger et al. 2017).

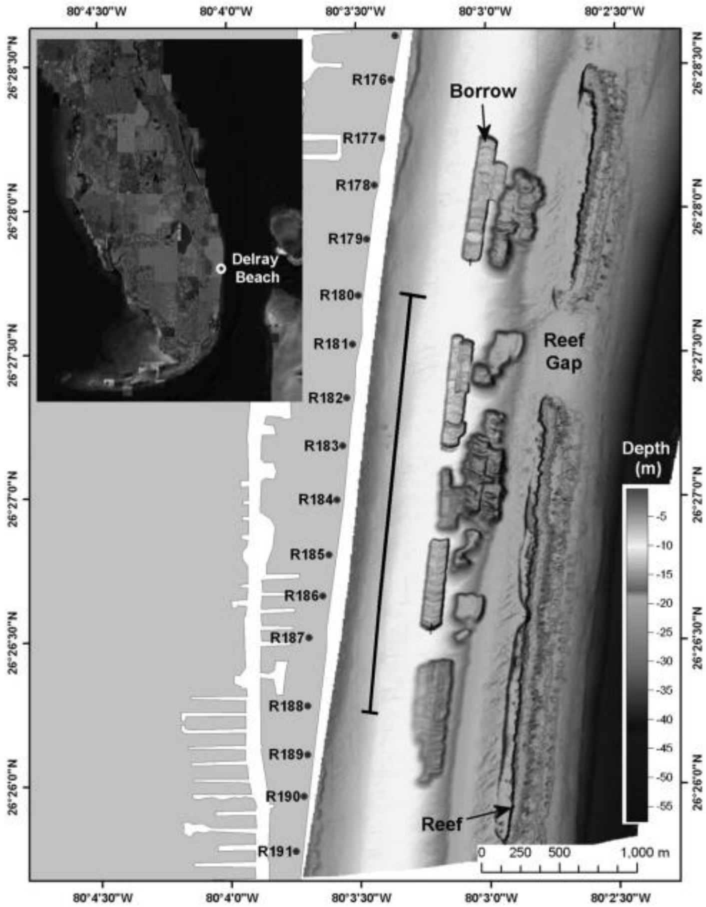

Figure 2.4 Bathymetric view of Delray Beach, Florida, displaying previous dredge pits and reefs (from Benedet & List, 2008) (Reproduced with permission from author).

Portions of the continental shelf are expected to contain large volumes of restoration quality sediment but have yet to be confirmed (Finkl et al. 1997; Finkl et al. 2007; Khalil et al. 2010; Khalil et al. 2018; Steele et al. 2019). Steele et al. (2019) reports the need for additional data coverage to further delineate and design preliminary borrow areas as viable sand sources along the Florida Atlantic and Gulf coasts. The Louisiana coast has had first-order surficial sediment distribution and volume maps created to display the distribution of sand, fine-grained sediment (silt, clays, etc.), and mixed sediment for the entire coast (Khalil at al. 2010; Khalil et al. 2018). Maps that identify sediment distribution like Louisiana's shelf have been recommended for all Gulf states (Khalil et al. 2018). Surficial sediment maps can help plan state-level planning and restoration efforts, guide state and federal agencies' protection of areas with high resource value and, prioritize removal or placement of energy infrastructure as to not interfere with valuable sediment resources (Khalil et al. 2010; Khalil et al. 2018).

The location, size, and depth of a dredge pit are considerations to minimize adverse impacts on adjacent beaches (Kaufman and Pikley 1983; Dean and Dalrymple 1991; NRC 1995; Work et al. 2004; Benedet and List 2008; Hartog et al. 2008; Benedet and List 2009; Taiani et al. 2012; Benedet et al. 2013) and promote desired infilling rates and grain size (Van Dolah et al. 1998; Jutte et al. 1999; Jutte and Van Dolah 2001; Greene 2002; Xu et al. 2014). The concept of reducing impacts on adjacent beaches through optimizing nearshore dredge pit design has been a focus of numerous inquiries (Taiani et al. 2012; Benedet et al. 2013). Changes in beach morphology can be caused by sediment transport potential variability around or due to a dredge pit (Benedet and List 2008; Hartog et al. 2008; Benedet and List 2009). Benedet et al. (2013) recommend alongshore-elongated shallow dredge pits with a narrow cross-shore width.

The infill rate and composition of sediment infilling dredge cuts have also been the subject of several studies. Van Dolah et al. (1998) evaluated five borrow areas in South Carolina and found that dredging at shallow depths led to less modification in wave energy and hydrodynamics at the site, reducing the infilling of fine sediment.

Estimated recovery times ranged between 1.75 years at a relatively small site to 11.8 years at a larger pit with an average of 6.8 years for all five sites. The study concluded that mined sites that refill with beach-compatible sediment are ideal to extend the life of the critical resource (Van Dolah et al. 1998). Therefore, dredge locations should target areas that have high rates of sediment transport of sand, such as depositional shoals, or bathymetric peaks, to promote rapid refilling of restoration quality sands (Van Dolah et al. 1998; USACE 2001; Greene 2002).

The continental shelf is ecologically important for many species. However, dredging results in direct mortality to the benthic infauna that live in the substrate (Jutte et al. 1999; USACE 2001; Green 2002; Byrnes et al. 2004; Wilber et al. 2009; Rosov et al. 2016; Wooldridge et al. 2016; Elko et al. 2020; Thompson et al. 2021). While benthic infauna are temporarily negatively affected by dredging, they often rebound to near normal levels within a relatively short amount of time (Van Dolah et al. 1994; Jutte et al. 1999; Posey and Alphin 2002; Peterson and Bishop 2005; Robinson et al 2005; Colosio et al. 2007; Rosov et al. 2016; Wooldridge et al. 2016). Numerous studies (CSA 2009; Wilber et al.2009; Rosov et al. 2016; Elko et al. 2020) note that best management practices should include dredging outside of peak larval recruitment season and conclude before the natural seasonal decline, use borrow areas that are compatible and likely to refill rapidly to reduce recovery times, and design pits optimized for short recovery times. Ultimately, when post-dredging conditions resemble pre-dredging conditions with morphology, sediment transport, and composition resembling normal conditions, repopulation of biota can be expected (Rosov et al. 2016; Elko et al. 2020).

Dredge and placement of material on beaches can also have an influence on the habitat for other species, such as nesting sea turtles where alterations to the morphology and impact nesting success (Andrew 1995; Rumbold et al. 2001; Dellert et al. 2014; Bladow 2017). Other species that are potentially impacted by dredging include highly migratory species such as the sandbar and blacktip shark. The sandbar shark is found off the coast of New Jersey from late spring to early fall to utilize nursery grounds (Springer 1960; McCandless et al. 2002; Rechisky and Wetherbee 2003). The State of New Jersey has set dredging windows for species of concern that include the threatened sandbar sharks (State of New Jersey 2021). Blacktips are known to aggregate in large numbers in the nearshore of South Florida in the winter and early spring which coincides with the primary dredging window (Kajiura and Tellman 2016). While they are considered a highly migratory species (Castro 1996; Kajiura and Tellman 2016), they are largely not considered when permitting shore and beach preservation projects (Section 161.072, Florida Statutes).

Gaps in the Knowledge

A A few primary gaps in the knowledge are suggested to be the focus of future work on the continental shelf. Several studies have suggested that additional geotechnical and geophysical investigations are needed to identify viable sources of sand along the coast (Finkl et al. 1997; Finkl et al. 2007; Khalil et al. 2010; Khalil et al. 2018; Steele et al. 2019). Further exploration and mapping of potential restoration quality sands is imperative for the future of coastal restoration and resilience efforts. The impact of storms on sediment ridges is partially understood when pertaining to formation and morphology, but additional information is needed on how ridge boundaries change in large storms on the shelf at various depths, as well as how long impacts last. Although small-scale investigations have occurred, large expanses of the Atlantic and Gulf continental shelves have not been evaluated for storm-driven changes at project-level scales. Additional study is needed to articulate best practices to preserve the boundaries and ridges so they can refill with the desired sediment to extend the longevity of the extremely valuable resource. Ideally, post-dredging physical conditions should closely resemble the pre-dredging conditions to promote a more rapid rebound from impacted benthic infauna (Rosov et al. 2016; Elko et al. 2020). And finally, ecological impacts of dredge and placement on certain keystone species are needed, such as further research on benthic infauna and migratory megafauna in the nearshore to improve best management practices.

Summary

The US Atlantic and Gulf continental shelves are incredibly valuable economic resources that have been well studied under normal and dredge conditions of generally lower wave energy. Under normal conditions, it is well-established that sand ridges are widespread from the nearshore to the shelf edge and are a product of local morphodynamic conditions with variability in their morphology and sediment composition. Sediment ridge formation most often requires an initial irregularity, sediment supply, sufficient sediment transport, and time. Once established, ridges can migrate several meters per year and are commonly composed of mixed siliciclastic and carbonate sediment with grain size distribution varying cross-ridge and vertically. Although sand ridge morphology and sediment boundaries are fairly well-studied under normal conditions, there is a large amount of area listed as “potential” in state and federal databases that require further exploration and research before permitting. Additional studies under normal conditions will likely yield even more detailed morphology and sediment distribution information valuable to permitting and leasing borrow areas.

Due to the unpredictable nature of storms and harsh in situ conditions, large-scale studies on storm-induced shelf changes have been insufficiently studied. Storm conditions increase sediment transport and assist in rapid ridge formation along with ridge maintenance, but rates vary widely and are functions of magnitude, orientation, and period of waves and currents. Storms are also linked to the evolution of shoreface-connected ridges. Storm-induced sediment transport can move sediment in the nearshore around inlets, structures, and offshore, often forming large sand waves between troughs and ridges. One of the largest gaps in the knowledge is with local storm conditions and the impact of storms on borrow areas due to sustained sediment transport.

Dredging can cause impacts to the shelf and adjacent beaches through changes in morphology, grain size, and sediment transport rates. The location, size, and depth of the dredge area are important aspects to continue minimizing adverse impacts on benthic infauna in the substrate and morphological changes to adjacent beaches and facilitate restoration quality sand infilling the pit. The sediment on the shelf, as identified under normal conditions needing further investigation, is the critical dredge material needed for restoration projects. Surficial sediment maps have been created for a number of states; however, more maps are needed to aid in additional state-level coastal restoration and resilience planning. Improvements to dredging practices should focus on the prevention of infilling of non-restoration quality sediment to extend the lifespan of borrow sources and maintaining physical conditions that resemble the pre-dredging conditions to allow for rapid rebound of benthic infauna.

In conclusion, the three main locations of further research as identified from the literature consist of 1) additional sand searches in under-investigated regions of the continental shelf, 2) a better understanding of storm impacts on hydrodynamic-driven ridge migration on the shelf, and 3) continuous improvements to best management practices as new information becomes available on dredging activities to enhance conservation of limited sediment resources and coastal environments.

CHAPTER 3: SEDIMENTOLOGY OF BEACHES IN NORTHERN PALM BEACH COUNTY, FLORIDA, USA

Introduction:

Beaches provide recreation, habitat, reduction of storm impacts, and serve as an economic driver. As these functions become threatened by erosion, a common solution is beach nourishment, which places sand on a beach to mitigate erosion and advance the shoreline seaward (Davis *et al.*, 2000; Dean, 2003). Understanding the implications of certain physical properties of sediment placed on beaches are important to ensure they continue to provide benefits and functionality. This study evaluates the 3-dimensional sediment characteristics and beach morphology along 12 km of beach in Northern Palm Beach County, Florida (USA) that includes segments with annual placement of beneficial use of dredged material (BUDM), periodic beach nourishment projects, and a non-nourished beach.

The borrow source sediment used for beach nourishment should be compatible to the native sediment (Houston, 2017). However, sediment properties can vary between common borrow sources such as inlets, offshore, or upland mines (Cisneros *et al.*, 2017; Dean, 2003). More than 95% of all sand volume placed for shore protection nourishment projects are through offshore dredging of compatible sediment (Dean, 2003). Offshore sources generally are reworked shelf sediments and sand ridges from previous sea levels (Finkl *et al.*, 2005), and dredging targets the layers most suitable for beach placement (Finkl & Khalil, 2005). Inlets are another source of beach sediment as many must be periodically dredged for navigational maintenance. Rather than offshore disposal, more recently in the US dredged sediment are placed on adjacent beaches as “beneficial use of dredged material” (BUDM). Sediments from inlets can consist of more poorly sorted sediment with larger grain sizes due to the accumulation of the larger sediments within the main channel (i.e., thalweg) resisting advection (Wang & Beck, 2012). Despite the different characteristics of inlet thalweg, placing sediment on the downdrift beaches keeps that sediment from being lost from the littoral system and mitigate erosional effects from the interruption of longshore sediment transport. Upland mines are another source of nourishment sediment but can have a smaller mean grain size and better sorting than typical beach sediment due to the dominance of terrestrial or paleoprocesses compared to the high-energy processes at the coast (OAI & CPE, 2012).

In the US, geotechnical studies of sediment suitability for nourishment are required prior to placing sand on a beach (USACE, 2019a & 2019b). However, over time, sediment properties on the beach might vary from the initial placed sediment due to selective transport (Blackley & Heathershaw, 1982; De Meijer *et al.*, 2002; Horn & Walton, 2007; Komar & Wang, 1994; Laceby *et al.*, 2017), storm-driven transport (Roberts *et al.*, 2013), or with recurring projects using different sediment sources (Laceby *et al.*, 2017). Certain textural and compositional sediment properties influence beach slope (Komar & McDougal, 1994; Kraus & Galgano, 2001; Karunarathna *et al.*, 2012; Leadon, 2015; McFall, 2019), permeability (Karunarathna *et al.*, 2012; McLean & Kirk, 1969; Reis & Gama, 2010), and substrate temperature (Milton *et al.*, 1997). Although generally accepted that grain size influences the angle of repose, and therefore beach slope (Komar & McDougal, 1994), Reis and Gama (2010) found that grain size is not entirely proportional to the beach face gradient. In contrast, McFall (2019) analyzed global beach sands and derived predictive equations for beach slope based on the sediment grain size (for median grain size of <1 mm). On open coastlines facing the dominant wave direction and not protected by coastal structures, classification was based on offshore significant wave height exceeding 12 hours per year ($H_{s,12h/y}$). Exposed beaches were identified as $H_{s,12h/y} > 3$m, moderately exposed as $H_{s,12h/y}$ between 1 and 3 m, and protected as $H_{s,12h/y} < 1$m. Predictions for each beach exposure were based on the inverse beach face slope (X):

$X = A\, d^{n}$ Equation 3.1

where d is median grain size in millimeters, A is a derived coefficient, and n is a derived exponent. The following equations were derived based on 181 samples to estimate beachface slope of each beach exposure type:

Protected: $X = 3.1\, d^{-1.1}$ Equation 3.2

Moderately protected: $X = 2.1\, d^{-1.8}$ Equation 3.3

Exposed: $X = 3.9\, d^{-1.85}$ Equation 3.4

The extent of wave runup can also be influenced by the slope and sediment size, with implications for the ecosystem services of beaches (Bascom, 1951; Wiegel, 1964; Dingler & Reiss, 2002). Increased wave runup from storms and increasing sea level will adversely impact sea turtle nests and increase mortality of eggs laid in low-lying locations (Fuentes *et al.*, 2010; Pike *et al.*, 2015). Sediment properties effect the success of sea turtle nests (Mortimer, 1982, 1990, 1995), influencing temperature (Andrew, 1995; Milton *et al.*, 1997; Turkozan *et al.*, 2011), moisture content (Andrew, 1995; Turkozan *et* *al.*, 2011), reflectivity (Andrew, 1995), oxygen exchange (Andrew, 1995; Chen *et al.*, 2010), and the slope conducive for nesting (Rizkalla & Savage, 2011; Turkozan *et al.*, 2011; Wood & Bjorndal, 2000).

Study Area

In Florida, 87% of the coast is considered “critically eroded” (FDEP, 2016) with more than 750 nourishment projects placing over 248 million cubic meters of sediment beaches since 1934 (Alabama State Board of Public Accountancy, 2022). Florida state regulations require that shore protection projects place no more than 5% of fine material on beaches and that sediment is compatible with the native beach sediment in composite mean grain size (Ousley *et al.*, 2014). Sediments on Florida’s large carbonate platform range from Jurassic to Holocene in age. Clastic material has been accumulating in quantities large enough to be observed with the carbonate since the Miocene from erosion of the Appalachian Mountains, transported via alluvial and coastal processes (Scott, 1997; Walker *et al.*, 1983). Many heavier minerals (e.g., less complex silicate polymers) are less resistant to erosion (Goldich, 1938) and result in fewer “heavies” found far from the source. The sediment found along the eastern coast of Florida is comprised of widely varying percentages from the alluvially transported provenance clasts (allochthonous), reworked shelf sediment (autochthonous), and biogenic clasts (autochthonous) (Goldich, 1938; Scott, 1997). Along large portions of Florida’s east coast, weathering of the coquinoid Anastasia Formation outcropping at the shoreline is also an important contributor of carbonate clasts.

This study focuses on the northern 12 km of Palm Beach County, FL, USA (Figure 3.1). Palm Beach County has both nourished and non-nourished beaches that are classified as intermediate with a longshore bar and trough morphology (Benedet *et al.*, 2006). The coquioid Anastasia Formation outcrops up to 2 m (NAVD88) on the beach and provides patches of sub-planar hardbottom in the nearshore. The dominant direction of longshore sediment transport is south, but seasonal reversals occur moving sediment north in the summer. The stretch of beach analyzed in this study are considered critically eroded (FDEP, 2016). The northern-most sites (R13A and R21) in the city of Jupiter is nourished annually with BUDM through a management plan adopted in 1997 to bypass 57,341 m^3 of sediment each year. Federally managed projects were constructed in 1995, 2002, and 2015 with a total of 1,047,440 m^3 of sediment placed (FDEP, 2021, and another project completed in early 2020. Numerous additional local projects have been constructed using sediment from upland sources (251,790 m^3), dredged material from the Atlantic Intracoastal Water Way (78,036 m^3), and sediment from an inlet sand trap (82,696 m^3) (Alabama State Board of Public Accountancy, 2022; FDEP, 2021). Juno Beach (R 27 and R34) is located south of Jupiter and has been nourished in 2001 and 2010 using offshore borrow sites placing a total of 1,847,311 m^3 of sediment (FDEP, 2021). The study also includes a non-nourished site to the south (R51).

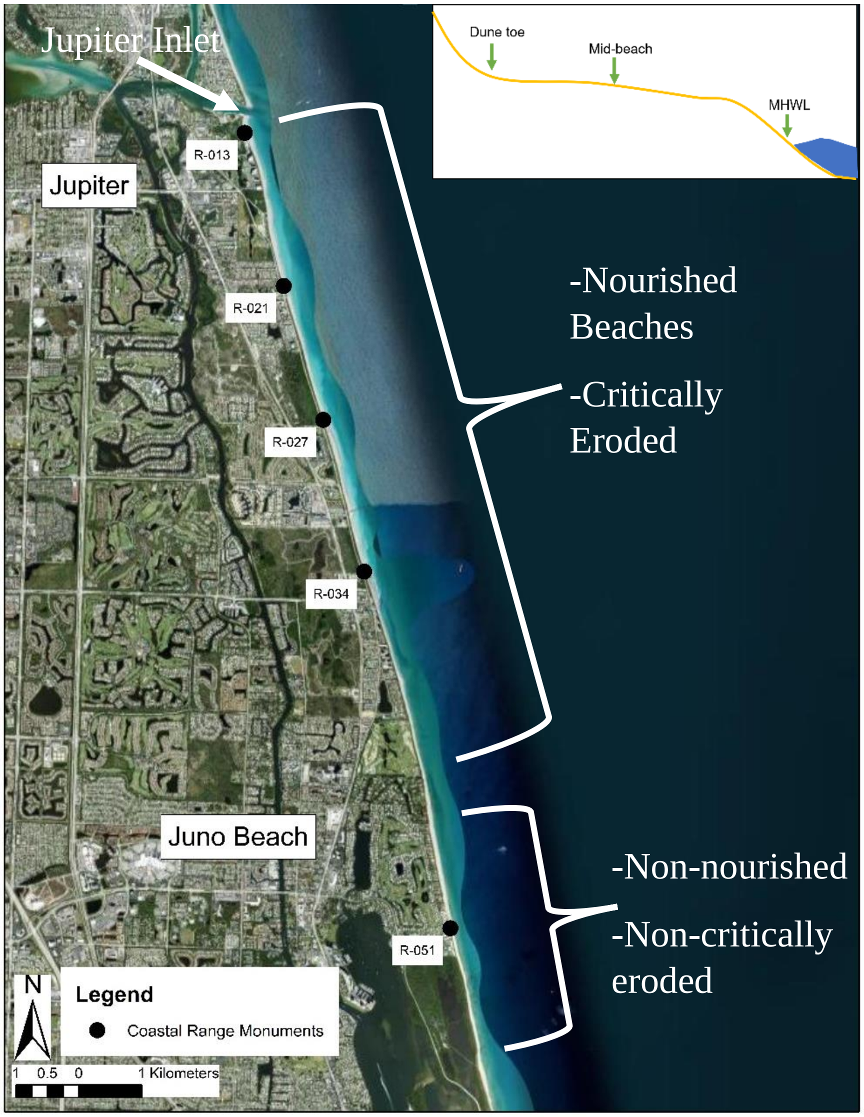

Figure 3.1 Study sites including nourished and non-nourished beaches in northeastern Palm Beach County, Florida, USA. Image of cross-shore sampling locations

Methods

Five locations were analyzed in the spring of 2019 along a 12 km study area, with transects spaced approximately 2 km apart from the Jupiter Inlet to just north of a state park (Figure 3.1). From north to south, the locations include an inlet-adjacent beach receiving annual BUDM (R13A), locations with periodic construction of shore protection projects (R21, R27, and R34) and a non-nourished control beach (R51).

A total of 30 sediment samples were collected at the surface (“S”) and at a depth of 75 cm (“75”) at the dune toe (high, “H”), mid-beach (mid, “M”), and Mean High Water Line (low, “L”) along the five transects and analyzed for composition and granulometric properties (Figure 3.1). Munsell color was determined for each sample and then sieved using a W.S. Tyler Ro-Tap Mechanical Sieve Shaker and Standard 8” full-height brass Test Sieves at half phi size intervals between -4 and 2 ϕ, and at quarter phi intervals between 2 and 4 ϕ. Percent carbonate was determined by hydrochloric acid dissolution. The remaining non-carbonate, siliciclastic fraction was then re-sieved. Statistical analysis was completed using the moment method to determine mean, median, standard deviation (sorting), skewness, and kurtosis for both the bulk sample and non-carbonate fraction (Boggs, 2014). Photos of the sediment samples and optical mineral analysis were conducted using a Leica M125 C microscope on bulk and non-carbonate fractions for all sediment samples. Qualitative observations were made for mineralogic composition, roundness, and a general identification of the carbonate fragments (e.g., bivalve, gastropod, coral).

Survey transects at the five locations were established using a Real-Time Kinematic Global Positioning System (RTK GPS). Beach profiles were collected using traditional level and transit procedures with a Spectra Precision Total Station from the seaward-side of the foredune to approximately 2-3 m water depth. Data from R21 to R51 were collected on 4/10/19. R13A was sampled on 5/8/19 because of an active BUDM placement project on the original sampling date. Foreshore slope at each transect was measured between approximately 1.0 m to -0.5 m elevation (NAVD88). Measured slopes were then compared with the McFall (2019) predictive equations for protected, moderately protected, and exposed beaches using the median grain size from the mean high water sediment samples.

Results

Bulk Sediment Properties

Surface sample sedimentology varied alongshore and cross-shore at each location (Figure 3.2). The most poorly sorted and coarse sediment was located at R13A. Downdrift, sediment generally became progressively finer and better sorted (except at the dune toe at R34). Sediment was coarser at the mid-beach than the dune toe, as expected. However, sediment at the MHW was the finest (except at R13A). At depth, increased sorting and fining downdrift was also measured (Figure 3.3). At depth, the cross-shore distribution of sediment followed the typical pattern of increased fining from the MHW to the mid-beach to the dune. Sediment at the non-nourished beach was similar to the nourished beaches (except at R13A).

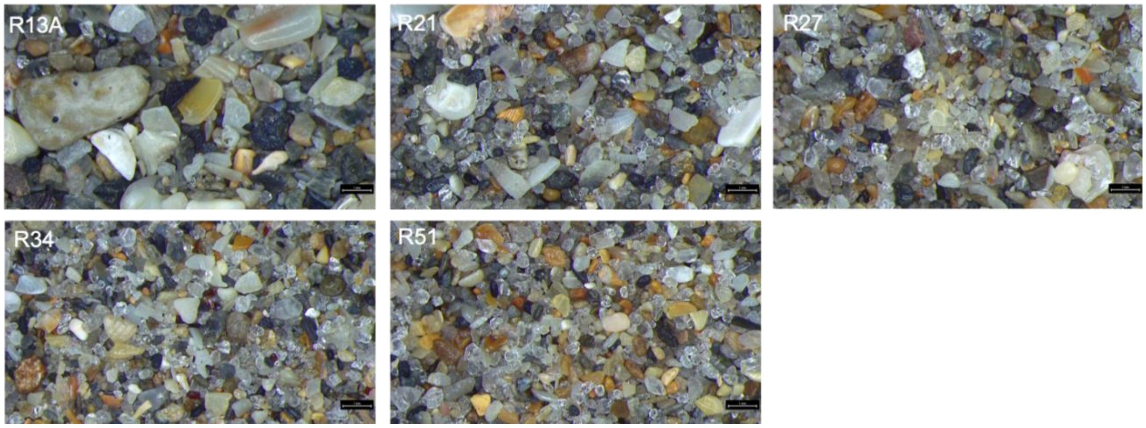

Figure 3.2 Example visual of the bulk fraction sediment at the surface from the mid-beach locations (10x zoom).

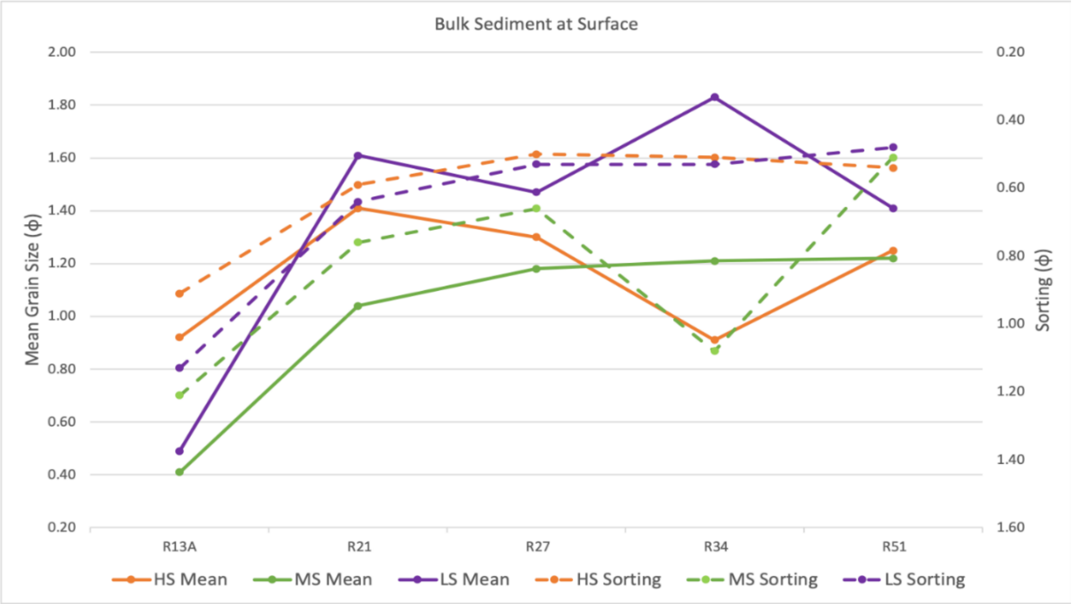

Figure 3.3 Surface sample mean and sorting at the high, mid, and low beach from north to south (R13A to R51)

Sediment at the Mean High Water (MHW) and mid-beach at the BUDM-influenced R13A were poorly sorted coarse sand (0.00-1.00 ±1.00-2.00φ). At the dune toe, sediment was moderately sorted (0.71-1.00φ) coarse sand at the surface and moderately sorted medium sand at depth (0.71-1.00φ). Surface sediment carbonate content increased from the dune to the MHW from 70%, 76%, and 82% at the dune, mid-beach, and MHW, respectively. At the MHW and mid-beach, carbonate content increased with depth to 84% and 78%, respectively. However, at the dune, the carbonate content decreased to 64%. A smaller grain size and lower carbonate content is expected for the aeolian-dominated dune toe, but also likely different due to the annual placement of shelly dredge material placed across the beach seaward of that location. All carbonate grains were sub-rounded, and consisted of bivalves, coral fragments, and semi-rare gastropods (Figure 3.4). Numerous large bivalve fragments along with other unidentifiable large fragments regularly exceeded 2 mm on the longest axis. The color of the sediments that were in this sample were light gray (5Y 7/1) and gray (5Y 6/1).

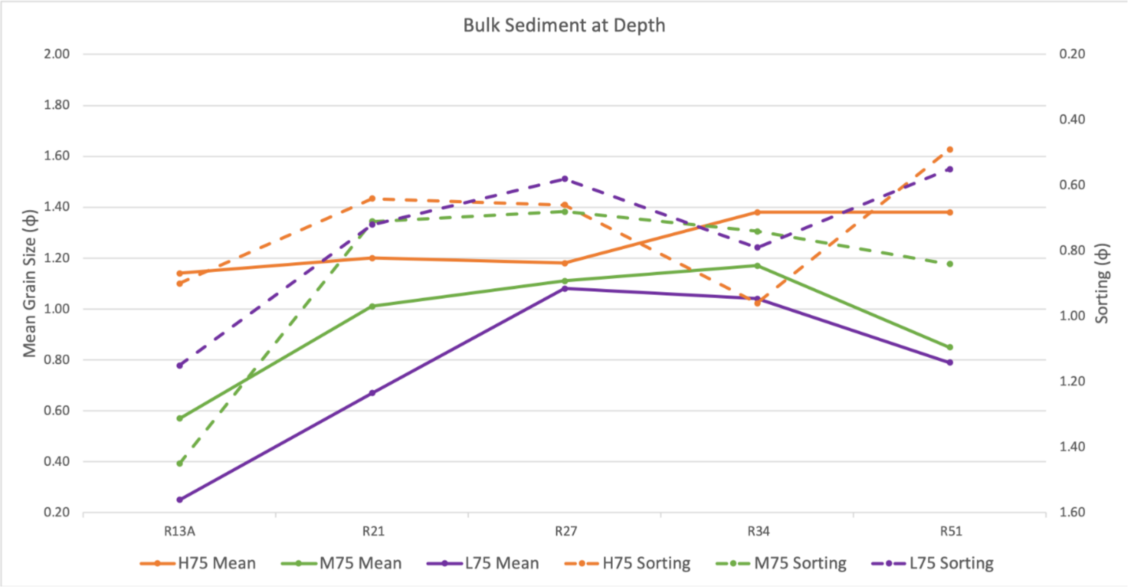

Figure 3.4 Mean and sorting of samples taken at 75 cm depth at the high, mid, and low beach from north to south (R13A to R51)

Sediment at most cross-shore locations at the nourished R21 transect were moderately well-sorted medium sand (1.00-2.00φ ±0.50-0.71φ) except for the mid beach surface sediment which was moderately sorted medium sand (1.00-2.00φ ±0.71-1.00φ) and the MHW sample taken at depth which was moderately sorted coarse sand (0.00-1.00φ ±0.71-1.00φ). Surface carbonate increased from the dune toe (47%) seaward to the mid-beach (59%) and increased with depth across the transect from 48%, to 55%, to 68% for the dune toe, mid-beach, and MHW, respectively. The exception to the overall increase was the MHW surface sample where the carbonate percentage decreased to 40%. Few carbonate grains exceeding 2 mm in length on the longest axis were measured at R21 with most grains being under this size (Figure 3.4). Carbonate materials were rounded to subrounded with some well-rounded grains. The color of the sediments that were in this sample were light gray (5Y 7/1).

Sediment at the nourished R27 transect were moderately well-sorted medium sand (1.00-2.00φ ±0.50-0.71φ). Sediment overall was finer on the surface than at depth across the transect. The carbonate at the surface was 46%, 47%, and 43% at the dune toe, mid-beach, and MHW, respectively. At depth, the sediment was higher in carbonate content than the surface and was highest in carbonate content near the dune with 58%, 54%, and 53% at the dune toe, mid-beach, and MHW. Carbonate grains rarely exceeded 2 mm on the longest axis and materials observed were rounded to subrounded with some well-rounded grains (Figure 3.4). The color of the sediments that were in this sample were light gray (5Y 7/1) and gray (5Y 6/1).

Sediment mean grain size at the nourished R34 transect were medium sand (1.00-2.00φ) with the exception of the dune toe surface sample that was coarse sand (0.00-1.00φ) (Figure 3.2). The sorting across R34 varied with the surface samples with moderately well sorted (0.50-0.71φ) at the dune toe and MHW, moderately sorted (0.71-1.00φ) at depth, and poorly sorted (1.00-2.00φ) at the mid-beach surface. Carbonate content for surface sediment was similar to R21 and R27 with 54%, 56%, and 43% for the dune toe, mid-beach, and MHW, respectively. At depth, the carbonate content increased seaward from 57%, to 58%, and 61% for dune toe, mid-beach, and MHW. The carbonate material rarely exceeded 2 mm in grain size on the longest axis and was found to be rounded to subrounded with some well-rounded grains (Figure 3.4). The color of the sediments that were in this sample were light gray (5Y 7/1) and gray (5Y 6/1).

Surface and at depth sediments at the non-nourished R51 at the dune toe were medium sand (1.00-2.00φ) (Figure 3.2). The mid-beach and MHW depth samples were coarse sand (0.00-1.00φ). The dune toe and mid-beach, and MHW depth sample were moderately well sorted (0.50-0.71φ), the dune toe at depth and MHW surface were well sorted (0.35-0.50φ), and the mid-beach depth sample was moderately sorted (0.71-1.00φ). A similar trend of carbonate content occurred across the beach with 50%, 53%, 48% at the dune toe, mid-beach, and MHW. Carbonate at depth was 48%, 66%, and 65% for the dune toe, mid-beach, and MHW, respectively, which was lower than other locations at the MHW. The carbonate material here rarely exceeded 2 mm in size and was rounded to subrounded with some well-rounded grains (Figure 3.4). The color of the sediments that were in this sample were light brownish gray (2.5Y 6/2).

Non-carbonate Siliciclastic Sediment Properties

The texture of the non-carbonate siliciclastic fraction was more similar cross-shore and alongshore at the surface than at depth (Figure 3.5). The dune toe and mid-beach sediments were coarser than the MHW, similar to the pattern observed in the bulk fraction. There was also an overall increase in sorting downdrift. Siliciclastic sediment at depth showed more variability that at the surface but followed the typical trend of coarser grains at the MHW as compared to the mid-beach or dune toe (Figure 3.6).

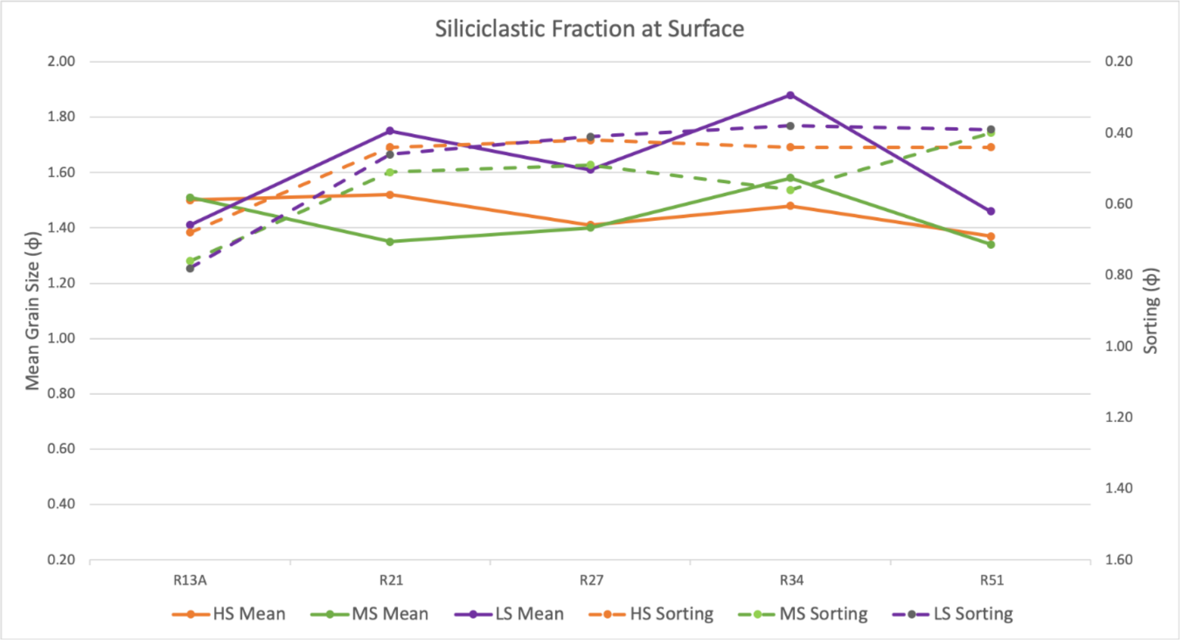

Figure 3.5 Non-carbonate siliciclastic mean and sorting of surface samples at the high, mid, and low beach from north to south (R13A to R51)

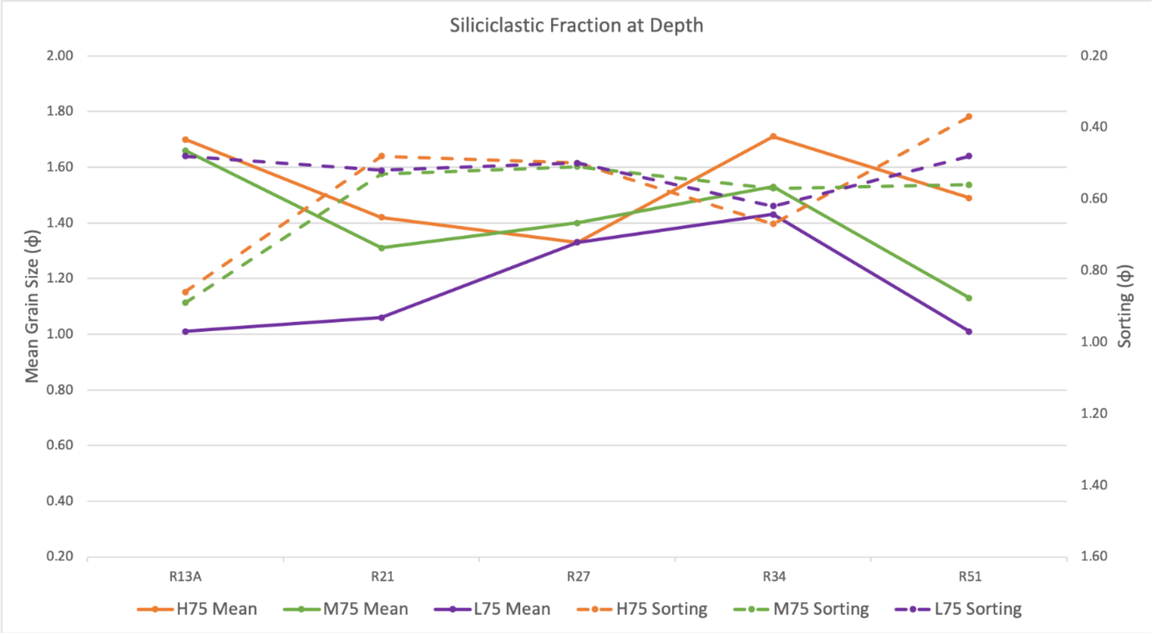

Figure 3.6 Non-carbonate siliciclastic mean and sorting of samples at 75 cm depth at the high, mid, and low beach from north to south (R13A to R51)

At R13A, sediment was generally moderately sorted medium sand (1.00-2.00φ ±0.71-1.00φ), with moderately well sorted medium sand (1.00-2.00φ ±0.50-0.71φ) at the dune toe surface and well sorted medium sand (1.00-2.00φ ±0.35-0.50φ) at depth at the MHW. Siliciclastic sediment from R21 were all on the border between well sorted and moderately well sorted (between ±0.44-0.53φ) medium sand (1.00-2.00φ). Sediment at the surface were finer than those at depth. At R27, sediment was well sorted (±0.35-0.50φ) medium sand (1.00-2.00φ) with moderately well sorted medium sand (1.00-2.00φ ±0.50-0.71φ) at depth at the mid-beach. Siliciclastic sediment at R34 were moderately well sorted medium sand (1.00-2.00φ ±0.50-0.71φ) with well sorted (±0.35-0.50φ) at the dune tow and MHW surface. At R51, sediment was well sorted medium sand (1.00-2.00φ ±0.35-0.50φ) with moderately well sorting (±0.50-0.71φ) at depth at the mid-beach.

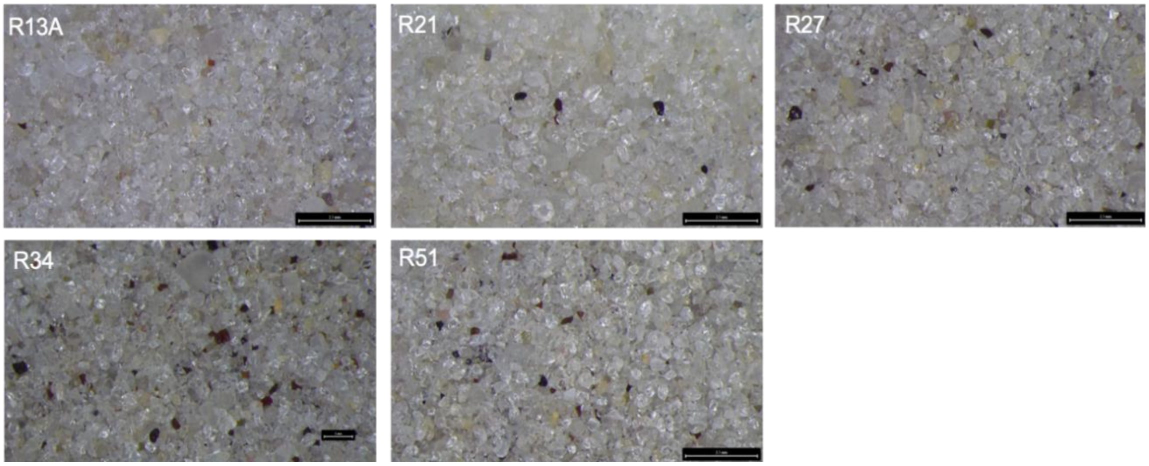

Figure 3.7 Example visual of non-carbonate siliciclastic fraction sediment samples at the surface of the mid-beach (10x zoom).

The non-carbonate siliciclastic sediment at all locations were relatively similar in appearance (Figure 3.7). The Munsell color of all sediments was white (2.5Y 9.5/1). Samples at R13A, R21, and R27 contained at least 95% clear or white silica and R34 and R51 contained at least 90% clear or white quartz. Sediment in the samples varied between rounded and subrounded in texture. The other grains that were not the white or clear silica consisted of black and infrequent other colored silica fragments (green, blue, purple, pink, reddish-brown) that were often smaller in size than the quartz grains.

Beach Profiles and Foreshore Slope

The two northern-most locations, R13A and R27 had a more overall convex shape and higher foreshore slopes as compared to the other sites (Figure 3.8). The beach at R13A was nourished with BUDM in April 2019, just prior to data collection, constructing a berm that was comparatively 20 m wider and the highest backbeach elevation. This location also had the steepest foreshore slope of 1:7 (vertical:horizontal). The foreshore at R21 was also comparatively steep, with a slope of 1:8. Between R27 and R51, beaches had an overall concave morphology with a seaward dipping planar foreshore. The dune at R27 extended ~8 m further seaward than other locations and R34 had a large scarp at roughly 10m. The foreshore slope at R27 was 1:11 and 1:12 at R34. Further south, the slope continued to decrease at R51 with a 1:14 slope.

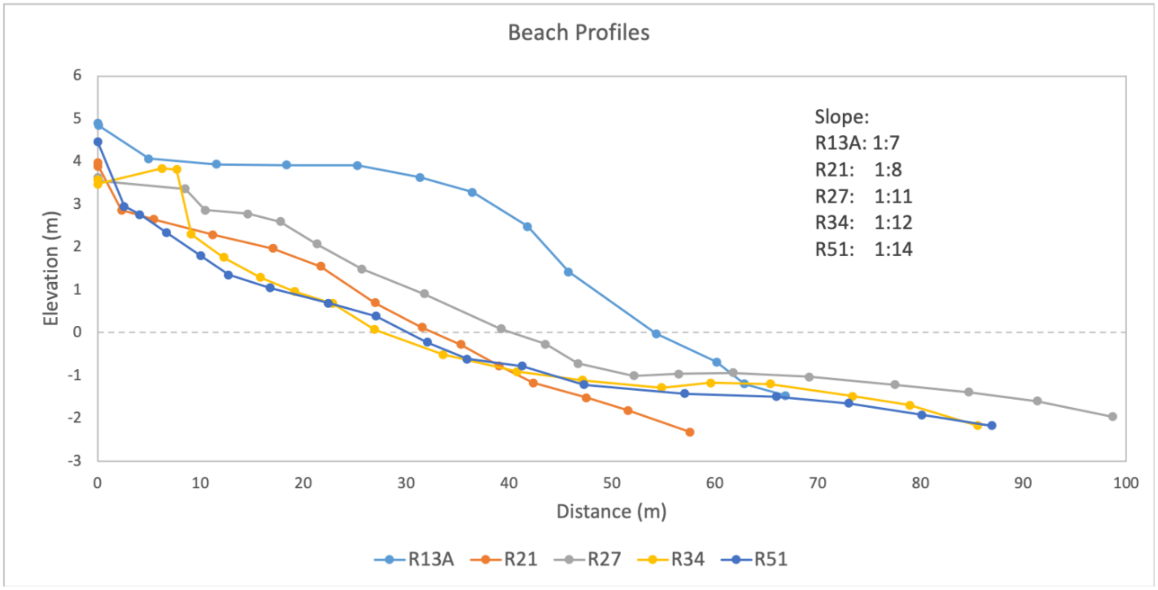

Figure 3.8 Beach profiles measured in the spring of 2019 at the five study sites.

The measured foreshore slopes were compared to the predicted slope under all three scenarios of exposure (Table 2.1). For all locations, the predictive equation for a protected beach most closely matched the measured slopes. At R13A, both the predicted and measured beach slope were 1:7. Although the measured slopes progressively became less steep to the south between R21 and R24, the predicted slope was the same (1:15). At the southern-most site, R51, the predicted slope of 1:13 nearly matched the measured slope of 1:14.

Table 3.1 Measured beach slope compared to predicted slope (best fit shown in bold)

Location	R13A	R21	R27	R34	R51
Median grain size (mm)	0.48	0.24	0.25	0.22	0.27
Measured slope	1:7	1:8	1:11	1:12	1:14
Protected (Eq. 2)	**1:7**	**1:15**	**1:15**	**1:15**	**1:13**
Mod. protected (Eq. 3)	1:8	1:30	1:30	1:30	1:25
Exposed (Eq. 4)	1:15	1:60	1:50	1:65	1:50

Discussion

Annual placement of coarse sediment from the adjacent inlet channel maintenance as BUDM resulted in the coarsest sediment at R13A. Whereas the beach and MHW locations had higher carbonate content and larger grain sizes due to the properties of the inlet thalweg, sediment at the dune toe was more similar to downdrift beaches because the BUDM were placed seaward of the dune. Sediment at the locations of shore protection projects were comparatively finer and better sorted than the sediment immediately adjacent to the inlet. The placement of ~2,300 m^3 of upland mined sediment at R21 in 2016 likely influenced sorting at this location as well as the immediately adjacent downdrift beaches (Cisneros *et al.*, 2017). The similar carbonate content at the shore protection project locations and the non-nourished beach are attributed to the local contribution of weathered coquina and autochthonous biogenic materials. Difference in surface samples and samples taken at depth illustrate that surface samples may not be representative of the entire 3-dimensional sedimentology of a beach. Samples at the non-nourished beach were similar to the beaches nourished with offshore or upland mined sand, suggesting that borrow source material is similar to the native sediment. However, different patterns in sediment properties were measured at R34, where a nearby marine life facility uses a water intake pipe extending across the swash zone. Additional study is recommended to evaluate the local hydrodynamics to determine any influence on beach sediments.

Finer sediment at the MHW surface as compared to the mid-beach and dune likely due to a recent accretionary event or beach recovery within the dynamic swash zone. Initial sediment transport onshore has been documented to consist of a finer fraction of sediment as compared to more energetic periods resulting in coarser materials, such as seen at depth (Roberts *et al.*, 2013). The difference in surface sediments and those at depth illustrate the dynamic nature of beaches, with spatio-temporal variability and selective transport of sediments placed as nourishment.

The non-carbonate siliciclastic sediment texture and mineralogy were similar between locations with either well sorted or moderately well sorted sand, except at the more poorly sorted BUDM location. The similarity of the siliciclastic fraction is attributed to extensive reworking of shelf sediment and weathering during regional-scale longshore sediment transport. Clasts varied in color, including black, dark brown, purple, blue, and green, and were present in nearly all the samples in some quantity. The black and dark brown mineral grains were likely ilmenite and magnetite. Ilmenite is not magnetic, with generally subrounded clasts, and is one of few minerals that is rather resistant to weathering. Other black mineral grains in the sample were magnetic. These grains are few in quantity but appear in R21, R27, and R34 that have been nourished using upland sediment source. The upland sediment may not have experienced the same degree of weathering rates as in an aqueous environment. This might also explain the presence of magnetite, a mineral with moderate ability to resist weathering, in a location far from any obvious source. The other blue, pink, purple, or a reddish-brown grains were likely “beach glass”, or heavily weathered broken glass (i.e., marine debris).

The beach slope prediction for protected beach exposure was closest to the measured slope at all locations. The combination of wave dissipation from the general bar and trough morphology and reduced fetch due to the large Bahamian archipelago contribute to the coasts’ protected nature. Where measured beach slopes ranged between 1:7 to 1:14, the predicted beach slopes ranged from 1:7 to 1:15. The predicted slope was the same as the measured slope at 13A. This site had the largest median grain size, but it was sample immediately following the placement of BUDM and would have been actively undergoing post-nourishment profile equilibration and not likely accreting (Willson *et al.*, 2017). The slope at the other locations were also very closely estimated by the protected beach exposure equation, except at R21. Although fine sediment is typically associated with more gentle slopes, it is likely that in this case the finer sediment at the MHW were from a period of onshore sediment transport resulting in a steeper foreshore. Therefore, caution is urged for predicting slopes using sediment collected during initial beach recovery (and perhaps immediately after major erosive events). Lastly, shallow or surficial outcropping bedrock at the shoreline and in the nearshore might have also influenced the foreshore slope in the area. Additional study is recommended to determine the role of antecedent geology, hydrodynamics, and timing of sampling events influence on local variability in sediment and beach slope.

Conclusions

This study evaluated the sedimentology and morphology of nourished and non-nourished beaches in northern Palm Beach County, FL, USA. Surface sample textures varied alongshore and cross-shore, with the most poorly sorted and coarse sediment located at the inlet-adjacent site influenced by placement of BUDM. Sediment generally became progressively finer and better sorted downdrift at the surface and at depth. At depth, the cross-shore distribution of sediment followed the typical pattern of increased fining from the MHW to the mid-beach to the dune, whereas the MHW surface sample was finer than the landward locations. The non-nourished beach sediment was similar to the beaches with sediment placed from either offshore or upland mines. However, the difference in surface samples and samples taken at depth illustrate that surface samples may not be representative of the entire 3-dimensional sedimentology of a beach, which can have implications for drainage, sediment transport, and habitat.

Finer sediment at the MHW surface as compared to the mid-beach and dune were attributed to a recent accretionary or beach recovery event highlighting the dynamic nature of beaches and spatio-temporal variability and selective transport of sediments placed during nourishment. Carbonate content at the shore protection project locations and the non-nourished beach were likely dominated by the local contribution of weathered coquina and autochthonous biogenic materials. The non-carbonate siliciclastic sediment texture and mineralogy were similar between locations (again, except at the site of BUDM), consisting primarily of quartz clasts and few other minerals. The similarity of the siliciclastic fraction is attributed to extensive reworking of shelf sediment and weathering during regional-scale longshore sediment transport.

Measured foreshore slopes were best predicted using the protected beach equation for this study area. The predicted slope was the same as the measured slope at the BUDM site, which has a larger median grain size and in an unlikely scenario of accretion, as it was likely undergoing post-nourishment profile equilibration. In contrast, the other locations had comparatively finer sediment at the MHW which would have resulted in more gently sloping beaches. However, finer sediment at the MHW was attributed to a period of onshore sediment transport resulting in a steeper foreshore. Thus, the complicated spatio-temporal morphodynamics of beaches should be considered when using median grain size from only one sampling event.

In summary, results from this study illustrate the 3-dimensional spatial variability of the sedimentology and morphology of natural and managed beaches. Future studies are recommended to evaluate the influences time-series sampling, nearshore hydrodynamics, and antecedent geology on beach sediments and morphology.

CHAPTER 4: BEACH AND NEARSHORE MORPHOLOGY AND SEDIMENT VARIABILITY RESPONSE TO DREDGE AND PLACEMENT

Introduction:

Beaches are widely recognized for their importance for recreation, habitat, reduction of storm impacts, and the economy. However, these dynamic coastal environments are increasingly threatened by erosion. Beach nourishment is a widely implemented method to mitigate erosion and advance the shoreline seaward (Davis & Barnard, 2000; Dean, 2003; Masselink & Gehrels, 2014). Understanding the erosional drivers when sediment is placed on beaches is important to ensure they can continue to provide benefits and functionality. This study aims to improve best management practices through a site-specific evaluation of time-series sediment and topo-bathymetric changes on inlet-adjacent beaches in response to dredge and placement events.

Beach nourishment, also known as a soft stabilization restoration method for coastal protection, is a nature-based solution (Bridges *et al.*, 2013; Bridges *et al.*, 2015a; Bridges *et al.*, 2015b) which is less disruptive to natural physical processes in the long-term as compared to hard structures and is generally less expensive (cites from bib on costs). Although sediment placed on beaches through nourishment practices is valuable, it is also a limited resource that will likely continue to increase in cost (cites needed from bib). While nourishment solves a localized problem of erosion, the sediment that is introduced temporarily modifies the natural forces in both the cross-shore and longshore directions (Dean, 2003). Coastal dynamics are already known to vary substantially along the world’s coastlines. Furthermore, specific cross- and longshore morphological changes vary with space and time. Therefore, detailed physical monitoring of site-specific coastal processes and morphology after subsequent nourishment projects are essential to quantify and predict nourishment performance along with gaining a more complete understanding of the causes of coastal erosion (NRC, 1995).

Factors that control nourishment performance vary spatially and temporally. Beach nourishment project success is often related to (but is not limited to) volume placed, the dry beach width or design template, and shoreline location (Hamm et al., 2002; Hanson et al., 2002 – need others). In Florida, beaches are especially important to the economy, habitat for many endangered species, and for storm protection. Florida beaches are frequently nourished with multiple factors influencing their success. In southeast Florida, Benedet et al. (2008) monitored a nourishment event and found the most significant influence on hotspot development was changes in shoreline orientation from the renourishment event which caused increased sediment transport potential as opposed to wave transformation over bathymetric irregularities. In west-central Florida, Roberts and Wang (2012) conducted a four-year monitoring of several beach nourishment events on three adjacent barrier islands and found the primary influence to be inlet processes directly impacting proximal beaches due to longshore transport interruptions. In an eight-year monitoring of a nourishment event in northwest Florida, Browder and Dean (2000) found nourishment event performance to be related most strongly to inlet proximity and storm occurrence.

This study evaluates sediment characteristics and beach topo-bathymetry along 12 km of beach in Northern Palm Beach County, Florida (USA) over two years. The study area is centered on the Jupiter Inlet and includes segments with annual placement of beneficial use of dredged material (BUDM), periodic beach nourishment projects, and non-nourished beaches. Bi-yearly surveys of beach and nearshore profiles and sediment were conducted from 2020 to 2021, totaling 60 profiles and 343 sediment samples extending from the dune toe to roughly -4 m water depth. Spatiotemporal variability in sedimentology and morphology were examined to evaluate the impact of multiple renourishment and storm events on the beach and nearshore system. The objectives of this study were to examine the impact of nourishment and storm events and identify the primary controlling factors on the beach-nearshore physical environment.

Methods

Study Area

The study area extended from 3 km north and 9 km south of the Jupiter Inlet (1) from the dune toe to ~200m offshore. A total of 15 transects were surveyed and sampled for morphology and sedimentology. PBC's nearshore is characterized by variable bar and trough (sandbar) morphology (Benedet et al., 2006) which includes extensive sandy bottom and hard bottom outcrops (primarily the coquinoid Anastasia Formation and relict Holocene coral reefs as part of the Florida reef tract) interspersed with depositional features up to 100m in width (Precht and Aronson, 2004; Finkl et al., 2005; Finkl & Warner, 2005). Mixed clastic and carbonate material comprises both the native and placed sediments from numerous beach nourishment projects in the microtidal, wave-dominated study area. Net sediment transport direction is to the south, which is interrupted by structured tidal inlets such as the Jupiter Inlet. Within the South Florida region and specifically in PBC, volumetrically small ebb-tidal deltas are asymmetrically skewed to the south (Stauble, 1993).

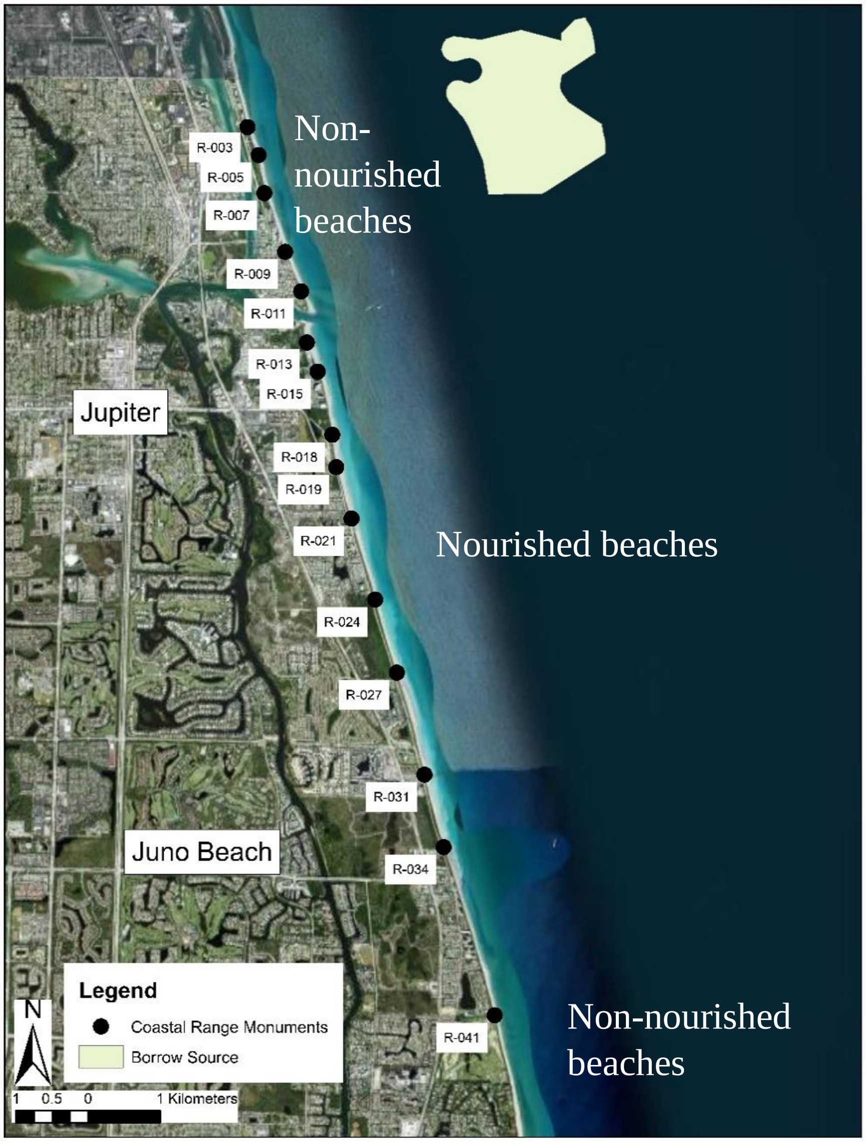

Figure 4.1 Study area containing both nourished and non-nourished beaches.

Beach nourishment is frequent in northern Palm Beach County as three nourishment events took place during this two-year study (FDEP, 2021). The inlet adjacent Jupiter Beach Park and Carlin Park receive BUDM placement when the inlet is dredged on a near-annual basis. In 2020, 451,924 m^3 of sediment was placed from R13.5-

R19 from an offshore borrow area as part of the North County Comprehensive Shoreline Protection Project (Palm Beach County Environmental Recourse Management [PBC-ERM], 2021a). Further south of the Jupiter Inlet from R26-R38, 917,465 m^3 of sediment was placed from an offshore borrow (PBC-ERM, 2021b). Also in 2021,162,085 m^3 (99,392 m^3 inlet sand trap, 68,809 m^3 Atlantic interior waterway, AIWW) of sediment was placed between ~R14 and R17 (PBC-ERM, 2021a).

Between 2020-2021, 22 wave events impacted the study area including seven named tropical storms of varying intensity and proximity (Tables 4.1 and 4.2), with 15 events in 2020 and 7 in 2021. Wave parameters are reported from the nearest wave station near Ft. Pierce, FL (# 41114) located approximately 80 kilometers north of the study area. Energetic waves were categorized based on a sustained max wave height of at least 2.25 m, roughly 2.5 times the average wave height. Five late winter and early spring wave events were recorded in 2020 in addition to tropical storms Bertha, Isaias, Sally, Teddy, Epsilon, and Eta, followed by two post-hurricane season wave events. The average wave height in 2020 was 2.91 m over a total of 351 hours with an average event sustaining >2.25 m wave height for 23.4 hours (Table 4.1). In contrast, four wave events occurred in late winter and spring of 2021 before tropical storm Anna and two subsequent fall wave events. The 2021 storms had an average wave height of 2.44 m for a total of 50 hours with an average event sustaining >2.25 m wave height for 7.1 hours (Table 4.2).

Table 4.1 Wave events and conditions recorded in 2020

					2020				
Name	Start Date	End Date	Max Wave height (m)	Wave height >2.25m (hr)	Dominate Wave Period	Peak water level (surge)(m)	Wind direction	Sustained wind (m/s)	Gust (m/s)
	1/10/2020	1/11/2020	2.63	28.5	6.70	1.03 (0.05)	ESE	8.6	17.8
	1/18/2020	1/18/2020	2.33	3.0	8.86	1.00 (0.19)	E	8.0	N/A
	1/21/2020	1/24/2020	3.88	49.5	11.84	1.38 (0.45)	WNW	5.2	12.4
	2/21/2020	2/23/2020	3.75	35.0	11.54	1.16 (0.31)	NNW	7.1	18.1
	3/8/2020	3/10/2020	2.62	26.5	15.17	1.18 (0.20)	E	8.2	16.5
Bertha	5/26/2020	5/26/2020	2.44	3.0	13.89	1.14 (0.23)	SSW	5.3	13.4
Isaias	8/2/2020	8/2/2020	3.69	14.5	8.80	1.11 (0.31)	NE	9.7	21.3
Sally	9/12/2020	9/12/2020	2.39	3.5	6.33	1.06 (0.16	SE	8.5	18.7
Teddy	9/20/2020	9/23/2020	3.34	70.0	12.90	1.57 (0.43)	NE	7.3	19.7
Epsilon	10/19/2020	10/19/2020	2.54	11.0	9.12	1.52 (0.27)	E	8.6	16.8
	10/21/2020	10/21/2020	2.30	0.5	11.11	1.38 (0.25)	SE	5.6	16.6
Eta	11/2/2020	11/3/2020	2.51	13.5	9.36	1.28 (0.26)	NE	7.6	19.3
Eta	11/7/2020	11/11/2020	4.23	81.0	9.94	1.19 (0.23)	E	10.0	24.2
	11/19/2020	11/19/2020	2.44	4.0	7.29	1.27 (0.17)	NE	8.1	16.5
NYE Storm	12/31/2020	12/31/2020	2.49	7.5	6.50	1.01 (0.06)	SE	10.3	14.9
		Average	2.91	23.4	9.96				
			Total hours:	351.0					

Table 4.2 Wave events and conditions recorded in 2020

				2021					
Name	Start Date	End Date	Max Wave height (m)	Wave height >2.25m (hr)	Dominate Wave Period	Peak water level (surge)(m)	Wind direction	Sustained wind (m/s)	Gust (m/s)
	3/7/2021	3/8/2021	2.75	21.0	8.92	1.08 (0.23)	NNE	10.7	19.2
	3/20/2021	3/21/2021	2.28	1.0	7.88	0.94 (0.23)	WNW	5.1	15.5
	4/2/2021	4/2/2021	2.29	0.5	5.26	1.11 (0.11)	N	7.3	17.6
	4/11/2021	4/11/2021	2.37	1.5	5.79	0.94 (0.07)	NNW	11.8	30
Ana	5/21/2021	5/21/2021	2.39	1.5	7.16	0.95 (0.13)	E	8.3	15.1
	11/20/2021	11/21/2021	2.76	23.5	8.84	1.30 (0.26)	ENE	6.4	15.8
	11/23/2021	11/23/2021	2.26	1.0	6.97	1.17 (0.21)	NNW	6.7	15.8
		Average	2.44	7.1	7.26				
			Total hours:	50.0					

Sampling Methods and Data Collection

Data collection as timed to coincide with natural and anthropogenic events expected to induce morphologic and/or sedimentologic changes to the beach and nearshore, such as storms, and nourishment. Beach profile surveys, bathymetric surveys, and sediment collection were conducted in the spring and fall seasons of 2020 and 2021. Topo-bathymetric surveys were conducted at 15 transects north (5) and south (10) of the Jupiter Inlet using Real-Time Kinematic Global Positioning System (RTK-GPS) and a vessel mounted echosounder mapping the dune toe to >200m offshore (Figure 4.1). The subaerial survey began at the monument located in the dune toe and extended seaward across the beach to the swash zone Variability in the foreshore slope was calculated between approximately 1.5 m to 0.5 m elevation (NAVD88) from the measured profiles. Bathymetry was collected using a single-beam, dual-frequency echosounder (SonarMite DFX) and processed using Hypack hydrographic software and ArcGIS. Bathymetry was collected along the same land survey transects. Contour and volumetric changes were calculated using the Coastal Engineering Design and Analysis System's (CEDAS) Regional Morphology Analysis Package (RMAP), evaluated above and above -3.0 m and 0.0 m elevation and half-meter intervals between 0.0 m and the monument (~ 4 m), respectively. Along with the transects, bathymetry was collected in between transects to capture nearshore morphology and portions of the ebb-tidal delta complex.

Surface sediment was collected at each of the 15 transects at the time of each survey at the mid-beach, shoreline, and at 50, 100, 150, and 200m depth contours within the surveyed area at each beach nearshore transect. Subaerial samples were obtained using a hand trowel to approximately 5 cm (~2 inchs) depth. Subaqueous samples were obtained using a 6x6” grab sampler deployed from the marine research vessel. Grain size distribution and statistics are determined from sediment analysis at half- and quarter-phi sieve intervals between -4 (16 mm) and 4φ (63 μm) using a mechanical Ro-Tap Sediment Shaker. Carbonate content was determined based on dissolution in a bath of diluted hydrochloric acid. The color was visually determined using the Munsell color chart. Missing samples are due to either hardbottom outcrop, limited access areas, wave breaks, or nourishment activities at the transect.

Locally elevated water levels are reported using measurements from Lake Worth Pier Station (# 8722670) located within PBC and wave parameters are reported from data collected at the nearest wave station near Ft. Pierce, FL (# 41114) located approximately 80 kilometers north of the study area. Energetic wave periods are classified as having a sustained max wave height of at least 2.25 m. Each event has an identified start date and end date, max wave height in meters, total time with waves over 2.25 m in hours, peak water level measured as a composite of high tide and surge, and wind information consisting of general direction, and velocity information including sustained and recorded gusts in m s^{-1}.

Results

The 15 profiles have been divided into subgroups based on geography and beach characteristics. R03, R05, R07, R09, and R11 are grouped into “North of Inlet” where all profiles were north of the Jupiter Inlet and have only had sediment placed in the dune (most recently 2021) except for emergency protective berms constructed in 2005 following the 2004 hurricane season and 2012 following Hurricane Sandy. Monuments R13A, R15, R18, and R19 are grouped as “Inlet Adjacent”. R13A and R15 are the most inlet adjacent profiles and are frequently subjected to the placement of BUDM on a near-annual basis. R18 and R19 are located at the attachment point of the ebb-tidal deltas terminal lobe and are also frequently nourished with seven projects in the past 20 years. Monuments R21, R24, R27, R31, and R34 are grouped as "Nourished open coast beaches". R21 and R24 are primarily maintained by the longshore sediment transport (LST) of the frequently nourished updrift beaches and through dune restoration. R21 also is adjacent and updrift of the heavily armored Jupiter Reef Club. R27, R31, and R34 are nourished often with three events in the past 20 years, most recently in 2021. R31 is adjacent and updrift of the Juno Beach Pier. Finally, R41 is the "control beach" where no sediment has been placed either through beach nourishment or dune restoration.

Beach Morphology

Alongshore variability of the morphologic change associated with each sampling event is presented and described from north to south.

Updrift (North) of Inlet

Beach profiles north of the inlet in the spring of 2020 consisted of a relatively tall dune and 30-40 m wide beach (Figures 4.2-4.6). After the 2020 storm season (i.e., summer into early fall), all profiles were vertically eroded (i.e., lower) with the largest vertical drop consisting of 1 m elevation loss and most of the change occurred at or below 3 m elevation. Following the active storm season, ridge and runnel were measured at all locations (Wang & Briggs, 2015). A mix of both recovery and erosional features were measured in spring 2021, composed of prominent ridge and runnel formations (R07, R09, R11) and scarps at other locations (R03 and R07). The last survey in fall 2021 recorded small amounts of erosion along the profile at R03 and R05 and accretion at the others (R07, R09, R11).

Downdrift Inlet Adjacent

Beach profiles downdrift of the inlet in the spring of 2020 consisted of morphologically monotonic recently nourished beaches ranging between 45 and 70 m wide (Figures 4.7-4.10). Initially, surveyed profiles had a relatively tall and steeply sloped dune. Post-2020 storm season, inlet adjacent accretion at R13A was attributed to sediment impounding from multiple storms' southerly wave approach (Briggs *et al.*, 2021. All other locations had erosion of the beach ~10 m landward. R15 was unable to be surveyed in the spring due to an ongoing nourishment project placing BUDM. R13A and R18 were eroded landward slightly and R19 had a small amount of accretion. In the final sampling event in fall 2021, all profile locations accreted sediment with R13A again gaining the most, likely due to impounding with the structured inlet north of it (Briggs *et al.*, 2021). The morphological response post-nourishment along the inlet adjacent transects was the familiar post-nourishment equilibration process of initial scarp retreat followed by adjustments to a more natural beach slope (Elko & Wang, 2007; Liu *et al.*, 2019; Roberts & Wang, 2012).

Nourished, Open Coast Beaches

Beach profiles measured in spring 2020 consisted of a dune between 3-4 m elevation and all locations had beaches steeply sloping seaward ranging from 18 to 28 m in width, except R31 where a 44 m wide berm was measured (Figures 4.11-4.15). The 2020 storm season eroded all profiles upwards of the 3.5 m elevation contour. In February 2021 a nourishment project was completed that included the R27, R31, and R34 locations building the beach further seaward. Updrift of the nourishment project, R21 and R24 had small amounts of accretion along most of the profile. Berm accretion/aggradation was measured in fall 2021 at R21 with aggradation of an active berm crest and foreshore at R34, both attributed to lateral spreading of the adjacent nourishment projects. In contrast, R24 and R27 had slight erosion measured with negligible change at R31.

Control Beach

The southernmost, non-nourished beach at R41 was generally a seaward-sloping planar profile (Figure 4.16). After the 2020 storm season, the beach was eroded upwards of 1 m below the 3.5 m elevation contour. Although remaining monotonic, the backbeach slope decreased with an increase in foreshore slope in spring 2021. The mid-beach berm extended seaward with upwards of 0.9 m aggradation advancing the shoreline 6 m in fall 2021.

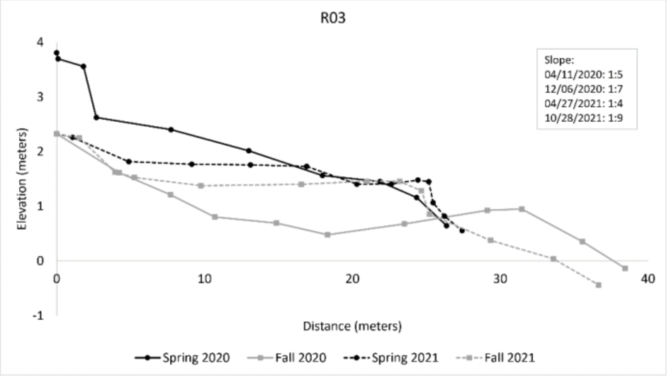

Figure 4.2 Beach profiles of R03

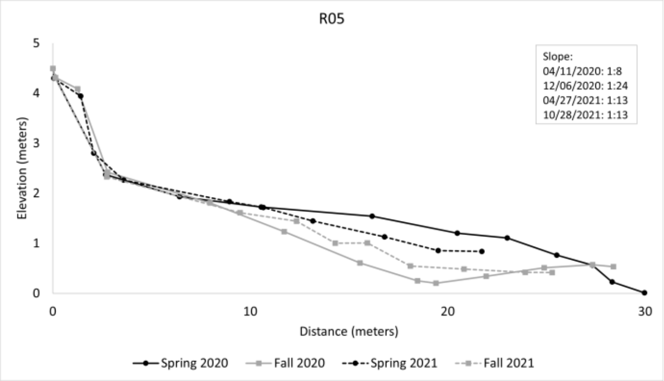

Figure 4.3 Beach profiles of R05

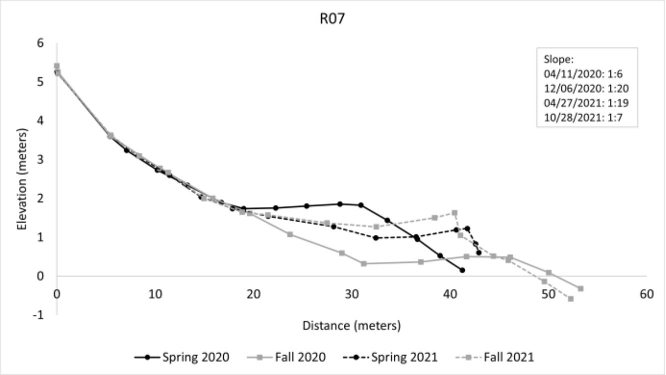

Figure 4.4 Beach profiles of R07

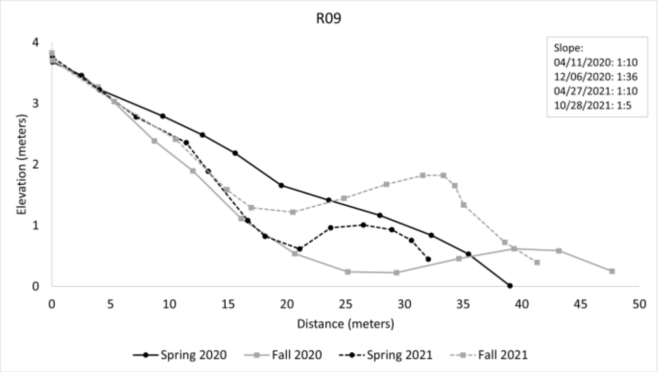

Figure 4.5 Beach profiles of R09

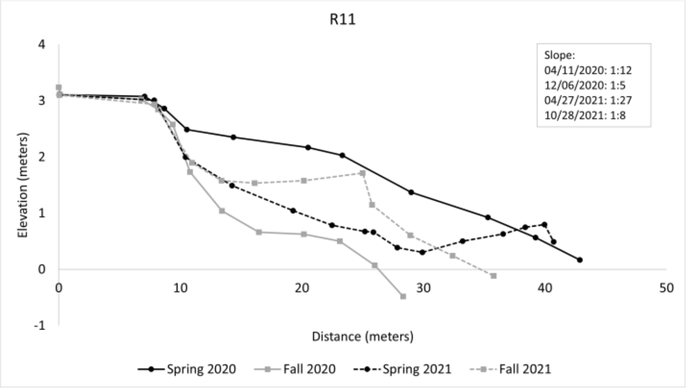

Figure 4.6 Beach profiles of R11

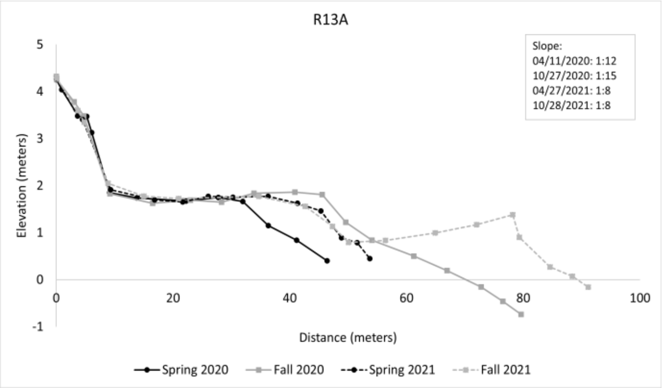

Figure 4.7 Beach profiles of R13A

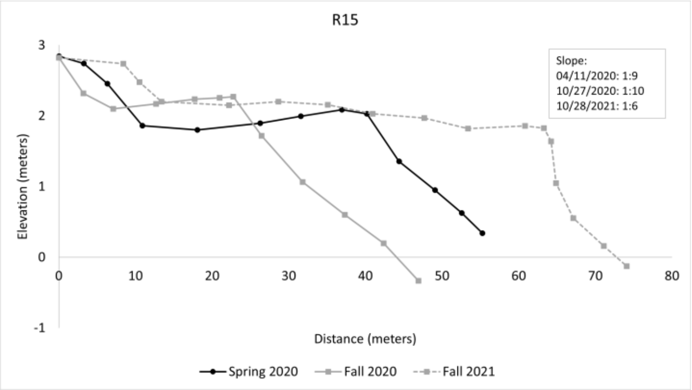

Figure 4.8 Beach profiles of R15

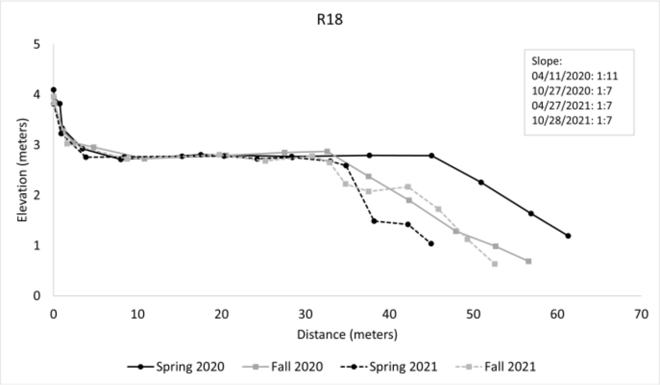

Figure 4.9 Beach profiles of R18

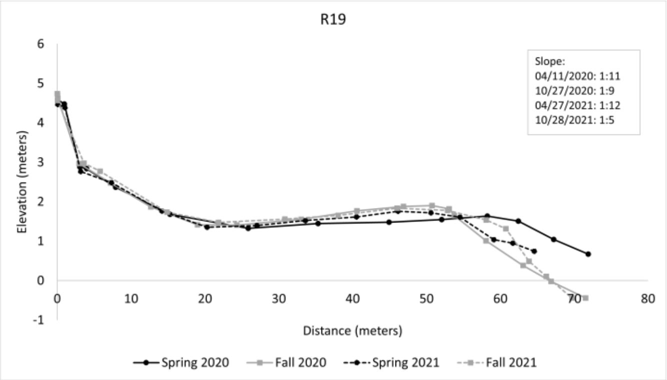

Figure 4.10 Beach profiles of R19

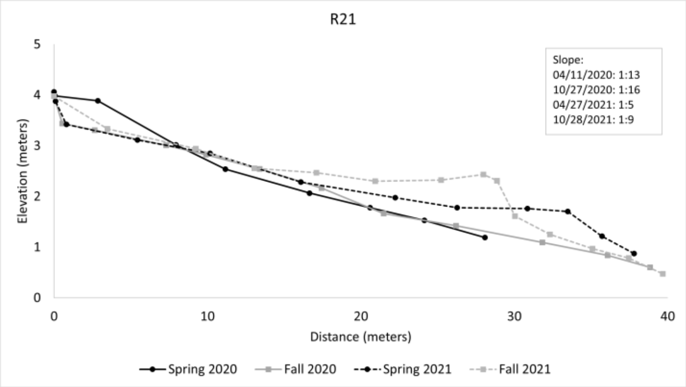

Figure 4.11 Beach profiles of R21

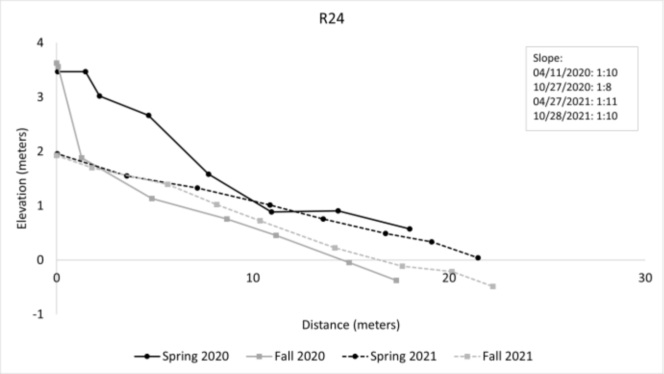

Figure 4.12 Beach profiles of R24

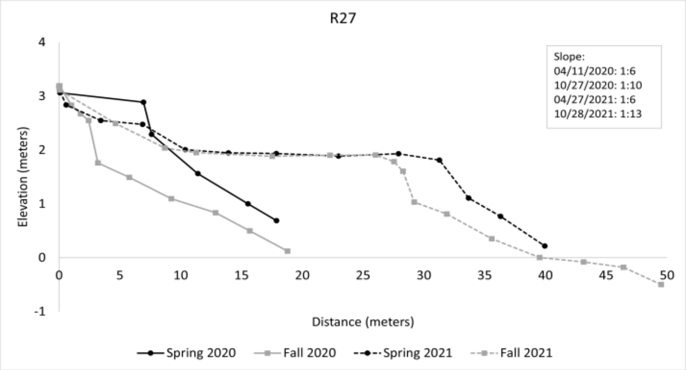

Figure 4.13 Beach profiles of R27

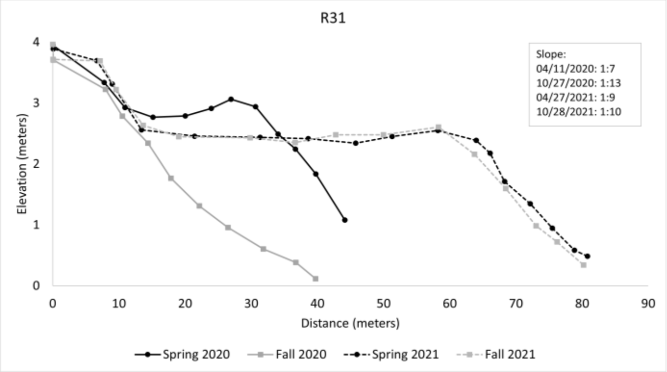

Figure 4.14 Beach profiles of R31

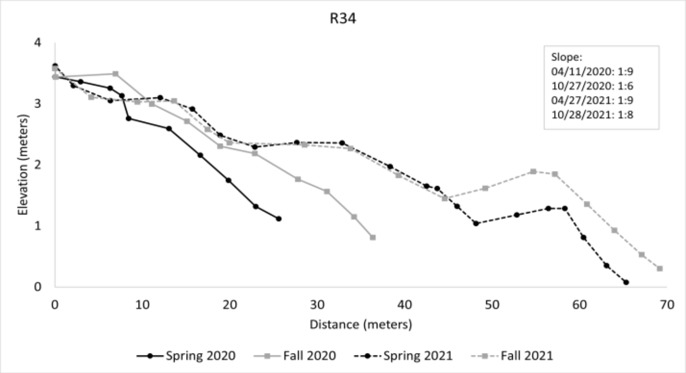

Figure 4.15 Beach profiles of R34

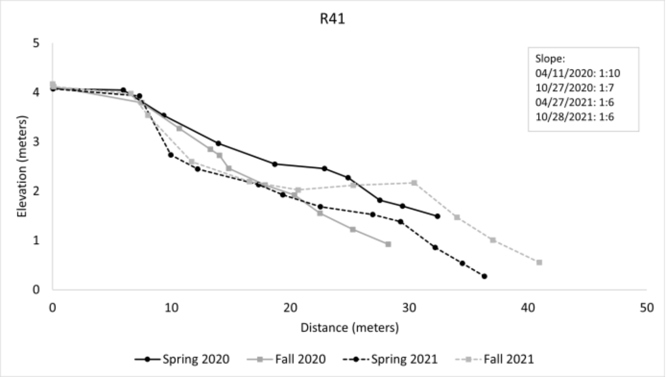

Figure 4.16 Beach profiles of R41

Bathymetry

Updrift (North) of Inlet

A single sandbar and trough feature was measured at R03 and R05 in spring 2020 but at variable distances from the shoreline (Figures 4.17 and 4.18). In contrast, an apparent double sandbar ridge and trough system was measured at R07 in spring 2020 (Figure 4.19) with no sandbar measured at R09 (Figure 4.20) or R11 (Figure 4.21). No data were collected in fall 2020 due to complete equipment failure (required a repair and replacement), and data was lost at all locations for the spring 2021 sampling event except at R11. Slight nearshore accretion was measured in spring 2021 at R11 but was eroded by fall. However, accretion was measured between spring 2020 and fall 2021 at R03 to R07, resulting in the disappearance of the sandbar at R05.

Downdrift Inlet Adjacent

The nearshore of R13A and R15 consisted of smaller undulating sand ridges with a very gently sloping offshore in spring 2021 (Figures 4.22 and 4.23). At R18 and R19, the nearshore steeply sloped to a trough separated from a portion of the ebb-tidal delta attachment lobe (Figures 4.24 and 4.25). However, where the survey truncates at the inclined ridge at R18, the crest of the attachment lobe is captured entirely by the survey at R19 (i.e., the attachment lobe was further offshore at R18 and closer to shore/attaching at R19). The inner surf zone was not captured in spring 2021 at R13A (see the straight area connecting the beach with the bathymetric survey) because of limited boat access within the guarded swim area. However, aggradation of the outer surf zone with an upward slope toward the ebb-tidal delta was measured. Slight nearshore accretion was also measured at R15 and R18 in spring 2021 resulting in trough-infilling at R18. An onshore migration of the attachment lobe was measured at R19. Little change was measured at R13A and R15. Changes at R18 were also minimal other than erosion in the outer surf zone. However, at R19 this change was more prominent with erosion and apparent offshore migration of the attachment lobe ridge and a wider trough.

Nourished, Open Coast Beaches

An apparent two sandbar system was measured in the nearshore at R21 in spring 2020 (Figure 4.26). A prominent sand ridge with a broad, deep trough was measured at both R24 and R27 in spring 2020 (Figures 4.27 and 4.28). Sandbars or sand ridges were not measured at R31 along an otherwise featureless offshore region (Figure 4.29). A relatively deep trough was measured in the inner surf zone at R34, with undulating sand ridges measured across the outer surf zone (Figure 4.30). In spring 2021, a single sandbar was measured at R21 with a larger sand ridges system forming at R24. However, the survey was truncated landward of the large ridge location at R27 with minimal changes measured otherwise. Although the broad trough remained, the ridge crest was eroded at R27 in fall 2021 in contrast to the negligible change measured at R31 and R34.

Control Beach

The nearshore at R41 was similar to the morphology measured at R34, with a deep, trough-like feature in spring 2020 and a largely flat, featureless outer surf zone (Figure 4.31). Little change was measured across the profile in spring 2021, with slight erosion measured in fall 2021 (also aligning with the measured change at R34).

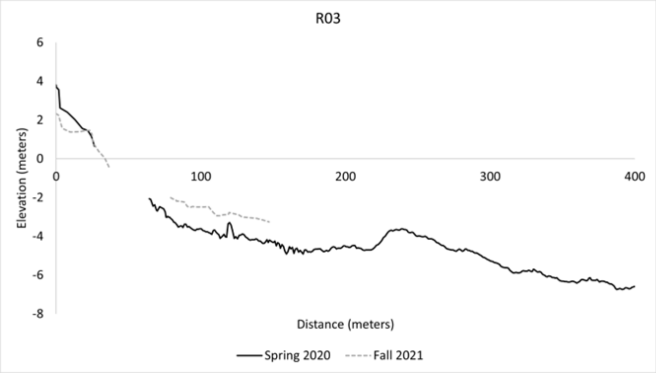

Figure 4.17 Topo-bathymetric profiles of R03

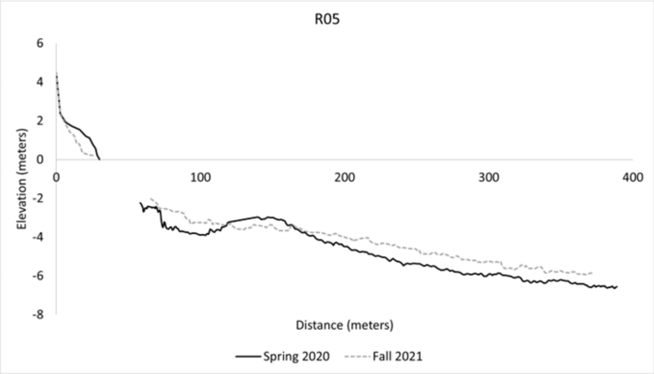

Figure 4.18 Topo-bathymetric profiles of R05

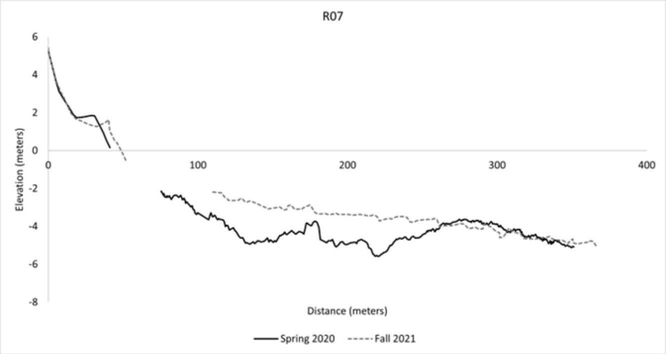

Figure 4.19 Topo-bathymetric profiles of R07

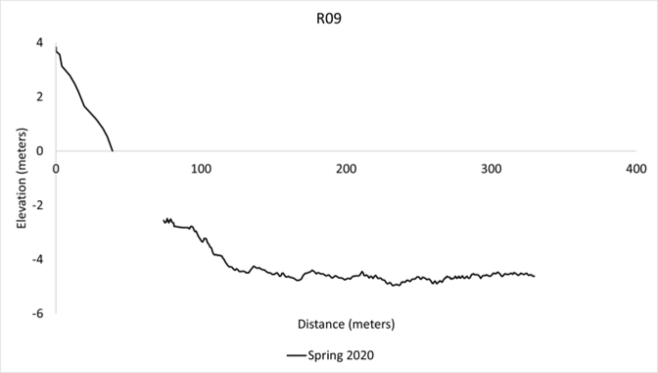

Figure 4.20 Topo-bathymetric profiles of R09

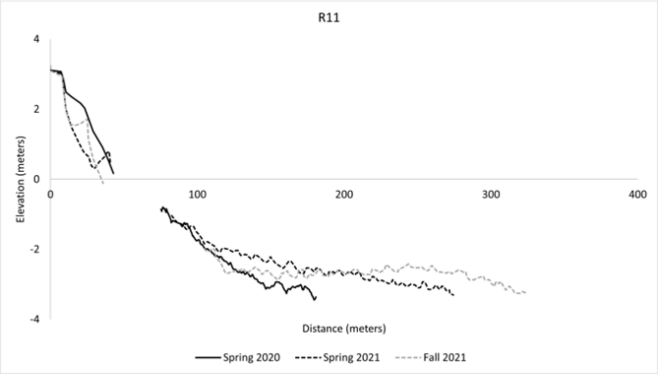

Figure 4.21 Topo-bathymetric profiles of R11

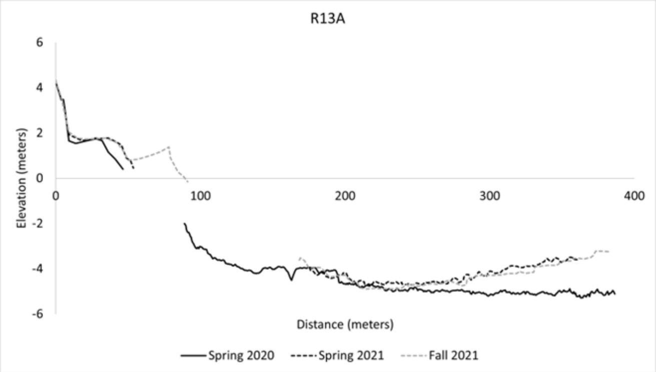

Figure 4.22 Topo-bathymetric profiles of R13A

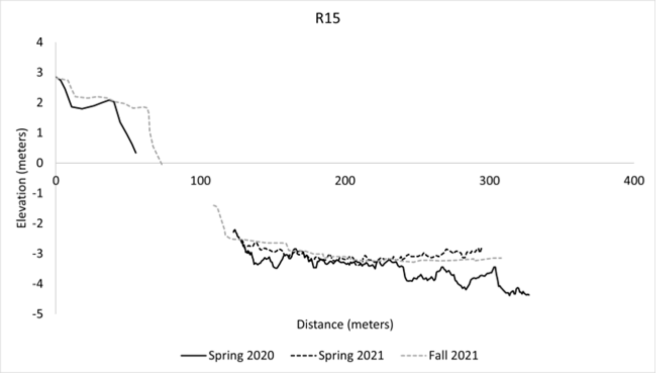

Figure 4.23 Topo-bathymetric profiles of R15

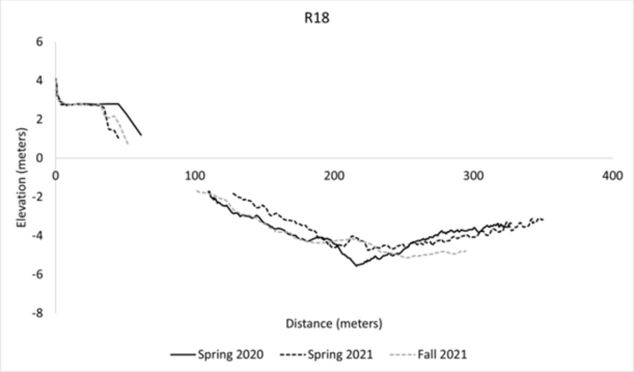

Figure 4.24 Topo-bathymetric profiles of R18

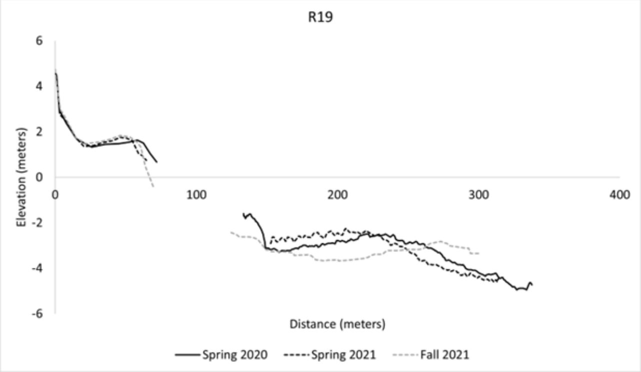

Figure 4.25 Topo-bathymetric profiles of R19

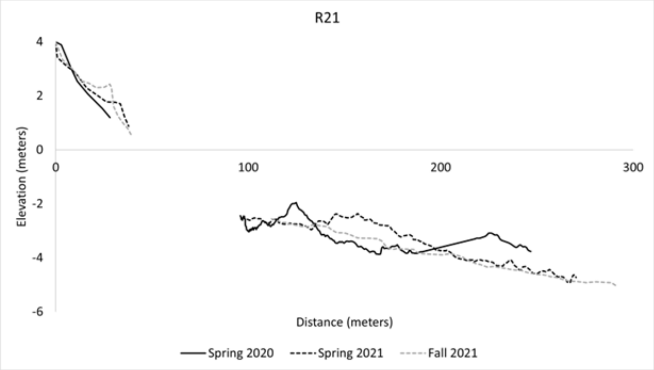

Figure 4.26 Topo-bathymetric profiles of R21

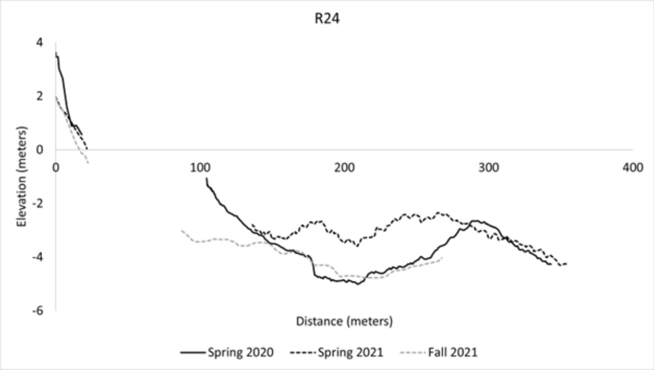

Figure 4.27 Topo-bathymetric profiles of R24

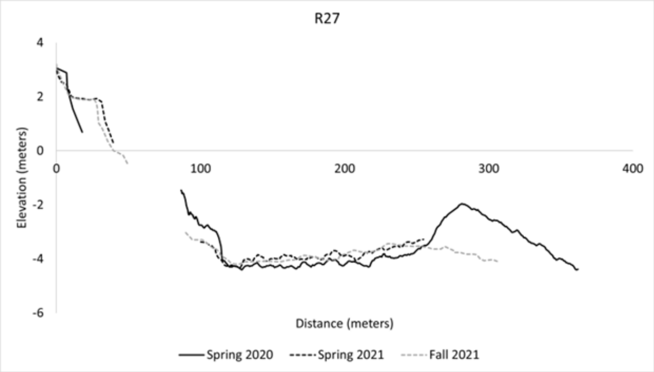

Figure 4.28 Topo-bathymetric profiles of R27

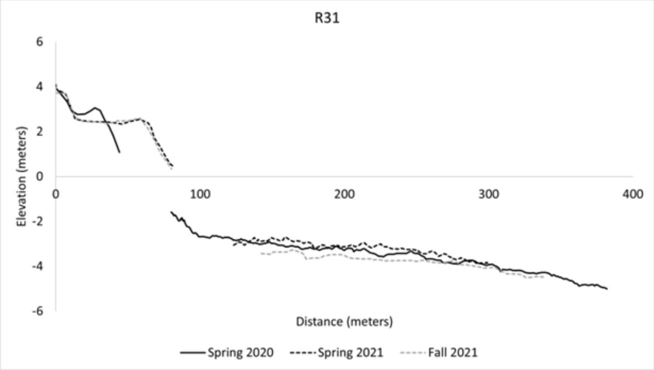

Figure 4.29 Topo-bathymetric profiles of R31

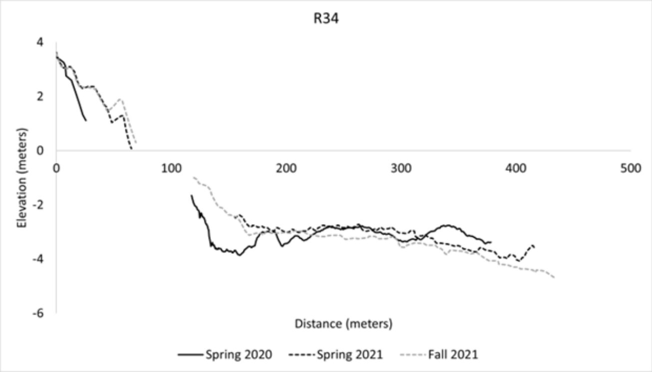

Figure 4.30 Topo-bathymetric profiles of R34

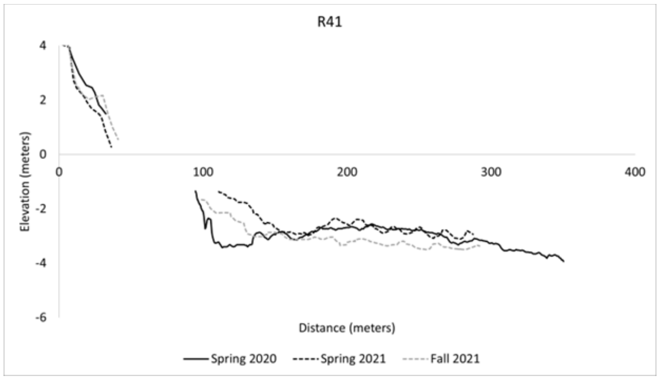

Figure 4.31 Topo-bathymetric profiles of R41

Sediment

Sediment mean grain size and sorting is presented alongshore and cross-shore for each sampling event for each group from north to south. In the following, beach sediments are those above the mean high water and nearshore sediments are those collected below the mean high water at the various distance intervals from the shoreline.

Updrift (North) of the Inlet

During the initial sampling event in spring 2020 north of the inlet, beach sediment was moderately well sorted (0.50-0.71φ) medium sand (1.00-2.00φ) (Figures 4.32 and 4.33). Nearshore sediment was more variable near the inlet (R09 and R11) ranging between coarse sand (0.00-1.00φ) and fine sand (2.00-3.00φ) that was largely moderately sorted (0.71-1.00φ) to moderately well sorted (0.50-0.71φ). The largest difference in grain size and sorting was sampled at the 200 m distance. In the fall of 2020 beach sediment was more variable in grain size and sorting ranging from moderately sorted (0.71-1.00φ) to moderately well sorted (0.50-0.71φ) coarse sand (0.00-1.00φ) to medium sand (1.00-2.00φ) (Figure 4.34 and 4.35). The nearshore sediment was less variable with moderately sorted (0.71-1.00φ) to moderately well sorted (0.50-0.71φ) fine sand (2.00-3.00φ). In contrast to spring 2020, the largest variability in nearshore sediment in fall 2020 was at the 50 m distance with sediment ranging from coarse sand (0.00-1.00φ) to fine sand (2.00-3.00φ). Beach sediment in spring 2021 was less variable with moderately well sorted (0.50-0.71φ) to well sorted (0.35-0.50φ) medium sand (1.00-2.00φ) compared to nearshore sediment that varied from moderately sorted (0.71-1.00φ) to moderately well sorted (0.50-0.71φ) medium sand (1.00-2.00φ) to fine sand (2.00-3.00φ) (Figures 4.36 and 4.37). However, in fall 2021, sediment on the beach ranged from moderately sorted

(0.71-1.00φ) to well sorted (0.35-0.50φ) coarse sand (0.00-1.00φ) to medium sand (1.00-2.00φ) in comparison to the moderately sorted (0.71-1.00φ) to moderately well sorted (0.50-0.71φ) medium sand (1.00-2.00φ) to fine sand (2.00-3.00φ) characterizing the nearshore (Figures 4.38 and 4.39).

In summary, sediment exhibited less variation and better sorting on the beach during the spring as compared to the fall when sediments were more poorly sorted. In contrast, the nearshore sediment was more variable with less sorting in the spring compared to the fall.

Downdrift Inlet Adjacent

The inlet adjacent locations exhibited some of the largest variability, likely from numerous sediment placement events that occurred over the study coupled with complex inlet-adjacent wave and current interactions (Wang *et al.*, 2011). Beach sediment in spring and fall 2020 ranged from poorly sorted (1.00-2.00φ) to moderately well sorted (0.50-0.71φ) medium sand (1.00-2.00φ) (Figure 4.32 and 4.33). Nearshore sediment ranged from poorly sorted (1.00-2.00φ) to moderately well sorted (0.50-0.71φ) coarse sand (0.00-1.00φ) to medium sand (0.00-1.00φ) in spring 2020, with greater variability in fall 2020 of poorly sorted (1.00-2.00φ) to moderately well sorted (0.50-0.71φ) very coarse sand (-1.00-0.00φ) to fine sand (2.00-3.00φ). The coarsest, most poorly sorted sediment was in the nearshore at R13A directly adjacent to the inlet. The beach sediment at R18 was more poorly sorted than in the adjacent locations. Sediment on the beach in spring 2021 was poorly sorted (1.00-2.00φ) to moderately well sorted (0.50-0.71φ) coarse sand (0.00-1.00φ) to medium sand (1.00-2.00φ) (Figure 4.36 and 4.37). Nearshore sediment ranged from very poorly sorted (2.00-4.00φ) to well sorted (0.35-0.50φ) very coarse sand (-1.00-0.00φ) to fine sand (2.00-3.00φ). Sediment at the inlet adjacent R13A remained very coarse along with coarsening at R15 and fining at R18. Beach sediment in fall 2021 was poorly sorted (1.00-2.00φ) to moderately well sorted (0.50-0.71φ) medium sand (1.00-2.00φ) to fine sand (2.00-3.00φ) (Figure 4.38 and 4.39). Nearshore sediment varied from very poorly sorted (2.00-4.00φ) to well sorted (0.35-0.50φ) gravel (-2.00- -1.00φ) to fine sand (2.00-3.00φ). Sediment at R13A was coarser than all previous sampling events.

In summary, beach sediment was consistently poorly sorted medium sand (except for fine sand sampled once at R15 in fall 2021 after nourishment construction). Nearshore sediment was more variable, with generally more poorly sorted coarse sediment and well sorted finer sediment. Patterns in sediment variability were influenced by multiple nourishment events.

Nourished, Open Coast Beaches

The nourished, open coast beaches exhibited more variable sediment characteristics, as well as more general geographic variability in addition to nourishment events. Beach sediment was moderately well sorted (0.50-0.71φ) medium sand (1.00-2.00φ) during spring 2020, except at R31 mid-beach that had coarse sand (0.00-1.00φ) (Figure 4.32 and 4.33). Nearshore sediment ranged from poorly sorted (1.00-2.00φ) to moderately well sorted (0.50-0.71φ) coarse sand (0.00-1.00φ) to fine sand (2.00-3.00φ). In fall 2020 beach sediment was moderately well sorted (0.50-0.71φ) to well sorted (0.35-0.50φ) medium sand (1.00-2.00φ) (Figure 4.34 and 4.35). Nearshore sediment varied from poorly sorted (1.00-2.00φ) to moderately well sorted (0.50-0.71φ) coarse sand (0.00-1.00φ) to fine sand (2.00-3.00φ). Beach sediment was more variable in spring

2021 with poorly sorted (1.00-2.00φ) to well sorted (0.35-0.50φ) coarse sand (0.00-1.00φ) and medium sand (1.00-2.00φ) (Figure 4.36 and 4.37). Nearshore sediment ranged from poorly sorted (1.00-2.00φ) to well sorted (0.35-0.50φ) coarse sand (0.00-1.00φ) to fine sand (2.00-3.00φ). At the 100m distance sample location at R27, sediment had a mean grain size of pebble (-3.87φ) consisting of ~98% gravel size shells. Sediment on the beach in fall 2021 was very poorly sorted (2.00-4.00φ) to moderately well sorted (0.50-0.71φ) medium sand (1.00-2.00φ) (Figures 4.38 and 4.39). Nearshore sediment varied from poorly sorted (1.00-2.00φ) to well sorted (0.35-0.50φ) medium sand (1.00-2.00φ) to fine sand (2.00-3.00φ). Sediment at the 200 m distance location at R24 was coarse sand (0.00-1.00φ).

Overall, sediment on the nourished, open coast beaches were most variable in the spring 2020 and fall 2021 but the least variable in fall 2020 and spring 2021. Nourishment in the winter of 2020-21 (between fall 2020 and spring 2021 sampling) introduced greater variability in sorting.

Control Beach

Beach sediments at the control beach (R41) were poorly sorted (1.00-2.00φ) to moderately well sorted (0.50-0.71φ) medium sand (1.00-2.00φ) in spring 2020 (Figures 4.32 and 4.33). Nearshore sediment was moderately well sorted (0.50-0.71φ) medium sand (1.00-2.00φ) to fine sand (2.00-3.00φ). In fall 2020, beach sediment was moderately well sorted (0.50-0.71φ) medium sand (1.00-2.00φ) with nearshore sediment that was moderately sorted (0.71-1.00φ) to moderately well sorted (0.50-0.71φ) coarse sand (0.00-1.00φ) to fine sand (2.00-3.00φ) (Figure 4.34 and 4.35). Sediment in spring 2021 was slightly finer and better sorted with moderately well sorted (0.50-0.71φ) to well sorted

(0.35-0.50φ) medium sand (1.00-2.00φ) on the beach and moderately sorted (0.71-1.00φ) to well sorted (0.35-0.50φ) medium sand (1.00-2.00φ) to fine sand (2.00-3.00φ) in the nearshore (Figure 4.36 and 4.37). Beach sediment in fall 2021 was moderately sorted (0.71-1.00φ) to moderately well sorted (0.50-0.71φ) coarse sand (0.00-1.00φ) to medium sand (1.00-2.00φ) and poorly sorted (1.00-2.00φ) to moderately well sorted (0.50-0.71φ) medium sand (1.00-2.00φ) to fine sand (2.00-3.00φ) in the nearshore (Figures 4.38 and 4.39).

In summary, sediment was consistently finer further offshore with medium sand on the beach except in fall 2021 when the mid-beach sediment was coarser. Sediment sorting was most consistent and best sorted in spring 2020 before the active hurricane season and nourishment construction.

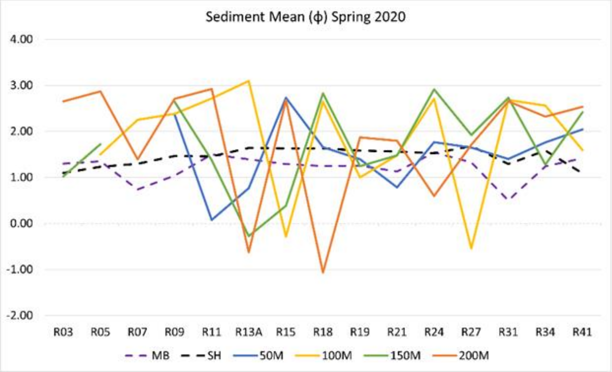

Figure 4.32 Sediment mean grain size, spring 2020

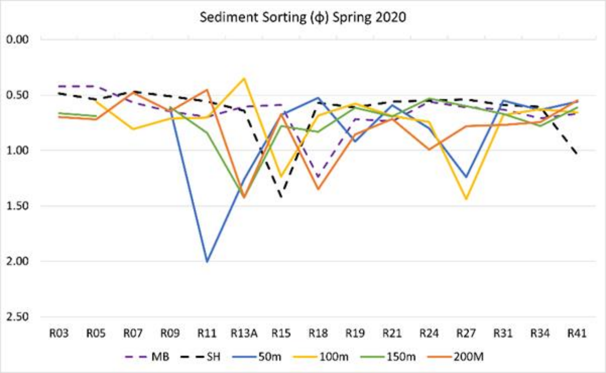

Figure 4.33 Sediment sorting, spring 2020

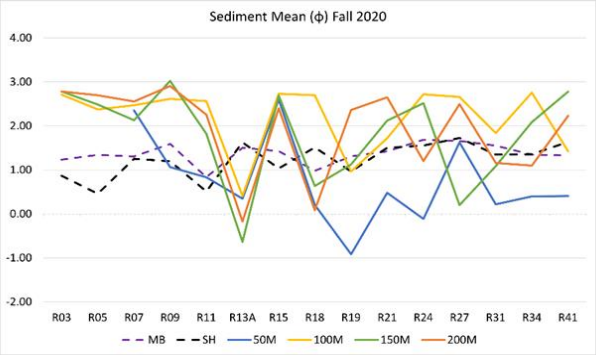

Figure 4.34 Sediment mean grain size, fall 2020

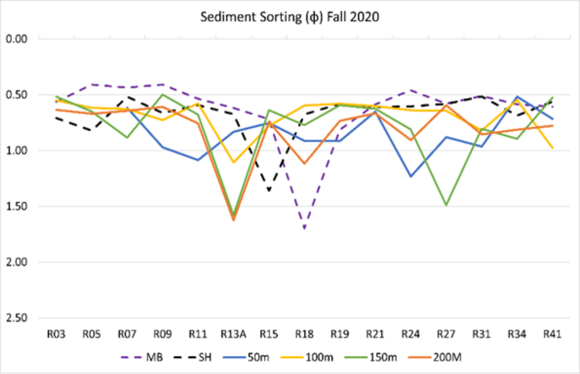

Figure 4.35 Sediment sorting, fall 2020

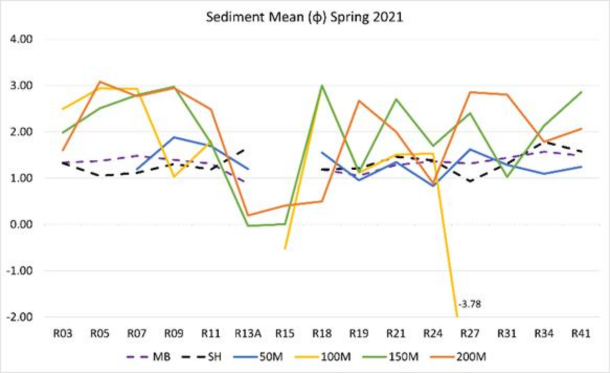

Figure 4.36 Sediment mean grain size, spring 2021

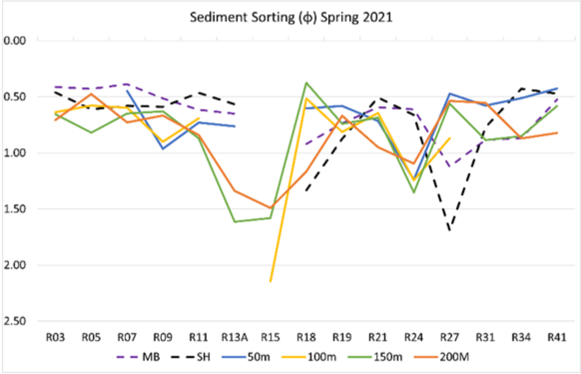

Figure 4.37 Sediment sorting, spring 2021

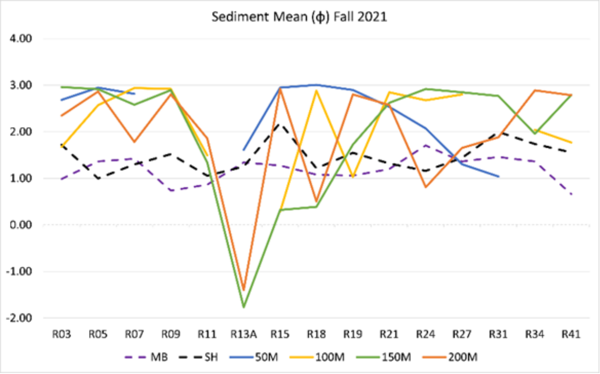

Figure 4.38 Sediment mean grain size, fall 2021

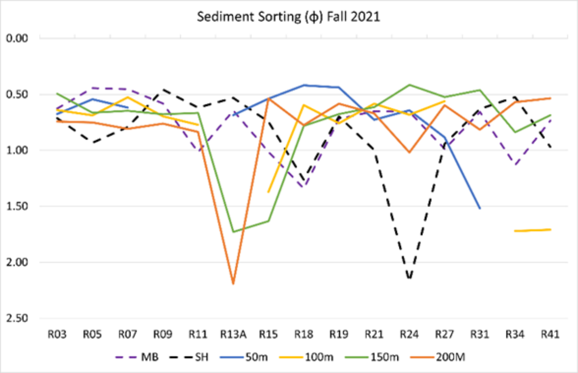

Figure 4.39 Sediment sorting, fall 2021

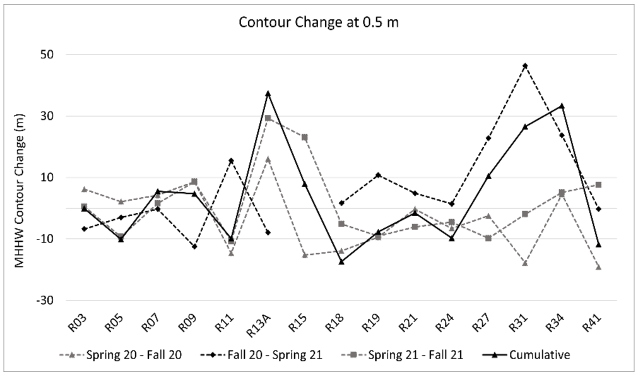

Figure 4.40 Contour change at 0.5 m (NAVD88)

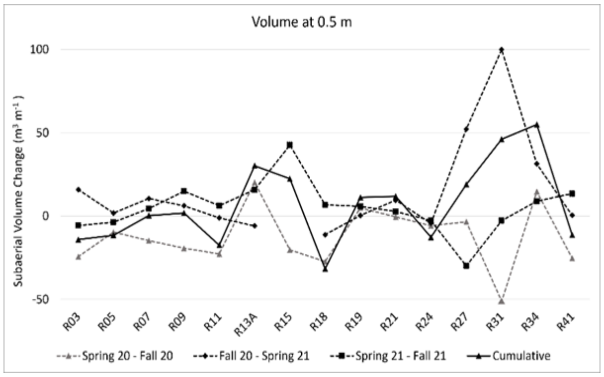

Figure 4.41 Volume change above 0.5 m (NAVD88)

Contour and Volume Change

Contour and volume change representing the dry beach was calculated above the 0.5 m elevation (NAVD88). Volume change across the entire profile was also evaluated above the -3.0 m elevation (NAVD88).

Despite the active hurricane season between spring 2020 and fall 2020, the beaches north of the inlet advanced upwards of 10 m seaward (R03, R05, R07, R09), except at the most inlet-adjacent location at R11 where the beach retreated landward 15 m (Figure 4.40). Along the downdrift inlet adjacent beaches, dry beach retreat was measured following the storm season ranging from 10 to 15 m, except at R13A where a 16m seaward advance was measured. Along the open coast beaches (nourished and non-nourished), the beaches retreated landward between 2 and 19 m, with the largest retreat measured at R31 and R41. Despite a seaward advance of the 0.5 m contour of the beaches north of the inlet, the volume decreased between 11 and 25 m^3 m^{-1} (Figure 4.41). At R13A, immediately south of the inlet, a volume gain of 20 m^3 m^{-1} accompanied the seaward advance. Despite contour retreat, the dry beach at R19 gained 9 m^3 m^{-1} of sediment volume. However, volume loss accompanied the dry beach retreat measured at R15 and R18 with 20 and 26 m^3 m^{-1} of erosion, respectively. Volume loss along the open coast beaches was more variable, ranging from 5 and 51 m^3 m^{-1} except at R34 which gained 15 m^3 m^{-1}.

The dry beach change measured between fall 2020 and spring 2021 was more influenced by winter storms and a nourishment event (Figure 4.40). North of the inlet, the dry beach retreated landward at R03, R05, R07, and R09, between 1 and 12 m, in contrast to 16m of seaward advance measured at the most inlet adjacent R11. These changes were of the same magnitude, but opposite direction as compared to the spring to fall 2020 changes measured. Immediately downdrift inlet-adjacent dry beach retreat of 9 m was measured at R13A. However, the seaward advance of 2 and 11 m was measured at R18 and R19, respectively. The nourishment event advanced the open coast beaches upwards of 46 m at R31 and 22m at both R27 and R34. Despite the contour retreat measured north of the inlet, beaches at R03, R05, R07, and R09 accumulated sediment between 2 and 16 m^3 m^{-1} of volume gain, except at R11 which had a negligible loss. Downdrift of the inlet, the dry beach at R13A and R18 had 6 and 11 m^3 m^{-1} of volume loss, respectively. The dry beach volume change was minimal at R19. The nourishment project resulted in between 10 and 100 m^3 m^{-1} volume gain along the open coast beaches at R21, R27, R31, R34, and R41. The largest volume gain was at R27 and R31 with 52 and 100 m^3 m^{-1}, respectively.

Between spring 2021 to fall 2021, the dry beach changes continued to be opposite but of the same magnitude for the beaches north of the inlet, where a seaward advance up to 10 m was measured at R03, R07, and R07 with a 10 m landward retreat measured at R11. South of the inlet, the beach advanced seaward at R13A and R15 advanced seaward 29 and 23 m, respectively, relating to BUDM placement. Landward retreat of between 5 to 7 m was measured at R18 and R19. Dry beach changes at the open coast beaches were variable with negligible change measured at R21, 5 to 8 m of advance at R34 and R41, and retreat ranging from 2 to 10 m at R24, R27, and R31. In contrast to the dry beach contour change, volume change north of the inlet was more variable, with less than 6 m^3 m^{-1} of volume loss at R03 and R05 but volume gain of 4 and 15 m^3 m^{-1} at R07, R09, and R11. Volume gain was measured at the downdrift inlet-adjacent beaches (R13A, R15, R18, R19) ranging between 6 and 42 m^3 m^{-1} with the most accumulation at R15 post-nourishment. The open coast beaches (R21, R34, and R41) with seaward advance also gained between 2 and 14 m^3 m^{-1} of sediment. Volume loss was measured at around 3 m^3 m^{-1} at both R24 and R27 a large loss of 30 m^3 m^{-1} was measured at R27.

The cumulative contour change at the northern locations was mixed with negligible change at R03, retreat at R05 and R11 both 10 m, and advance at R07 and R09 of approximately 5 m. Inlet proximate locations R13A and R15 had shoreline advance of 37 and 8 m respectively, while R18 and R19 had shoreline retreat of 17 and 8 m, respectively. At the southern locations, the cumulative change was mixed with accumulation occurring at R27, R31, and R34 ranging from 11 to 33 m. The beach at R21, R24, and R41 all retreated landward between 2 to 11 m. Cumulative volume changes at the northern locations yielded primarily losses at R03, R05, and R11 ranging from 11 to 17 m^3 m^{-1} and insignificant accumulation at R07 and R09. Locations proximate to the inlet accumulated sediment at R13A, R15, and R19 between 11 and 30 m^3 m^{-1} with the most accumulation toward the inlet, and 31 m^3 m^{-1} sediment was eroded at R18. In the southern locations, the volume was like the contour change with increases in volume at R21, R27, R31, and R34 between 12 and 55 m^3 m^{-1} increasing at each location down drift and losses at R24 and R41 of approximately 12 m.

The cumulative change along the entire profile above -3.0 m (NAVD88) over the two years was variable. The northern profiles extended seaward at R03 and R07 51 and 79 m, respectively, and retreated landward at R05 56 m. Around the inlet, all profiles extended seaward with the most occurring at R11 of 160 m and the rest ranging between 7 and 59 m except R18 which retreated 4 m (Figure 4.42). The southern locations all had landward retreat between 17 and 231 m except for R21 which extended 47 m.

Cumulative volume change was positive at the northern lines (R03, R05, R07) ranging from 3 to 66 m^3 m^{-1} (Figure 4.43). Around the inlet, volume change was variable with increases at R11, R13A, R15 of 29, 177, and 44 m^3 m^{-1}, respectively, and decreases at R18 and R19 of 54 and 87 m^3 m^{-1}, respectively. The southern profiles were mixed with increased sediment at R21, R31, and R34 ranging from 105 to 142 m^3 m^{-1} and decreased volume at R24, R27, and R41 188, 51, and 27 m^3 m^{-1}, respectively.

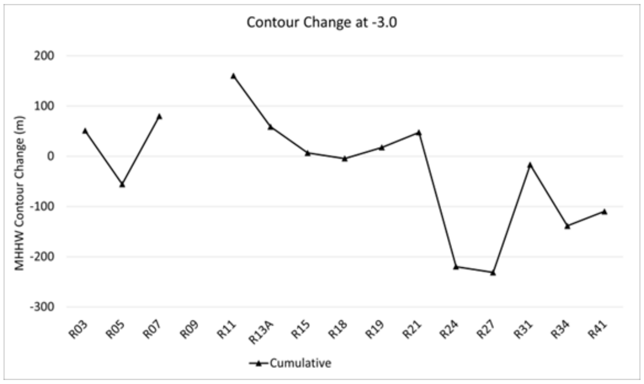

Figure 4.42 Contour change at -3.0 m (NAVD88)

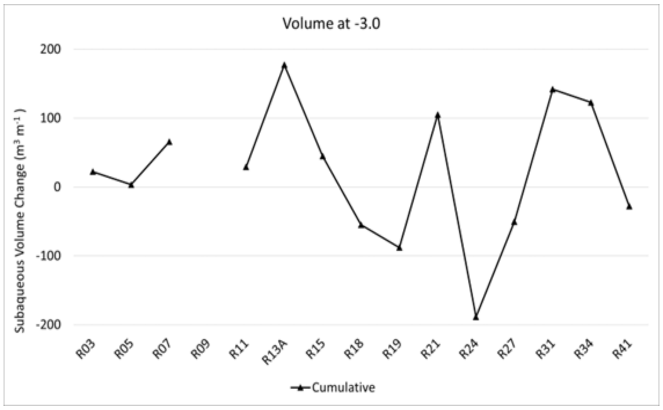

Figure 4.43 Volume change at -3.0 m (NAVD88)

Discussion

In general, the study area consisted of moderately wide beaches that had little change in subaerial grain size and sorting. The beach-nearshore system was most strongly influenced by a combination of inlet processes and migrating sediment ridges dominated changes in the nearshore. Sediment offshore was consistently finer in troughs and coarser on both ridges and near inlet features and became coarser after beach nourishment and high-energy wave events. Subaerial beach sediment was comprised of coarser, more poorly sorted sediment near the inlet and finer sediment downdrift (consistent with the trends observed in 2019, Chapter 3). Each sampling event of the two-year study period was influenced by high-energy natural forces, beach nourishment, or both which dominated the spatiotemporal patterns of variability. The largest impacts on the study area included the high wave energy nearly year-round, with two hurricane seasons shouldered by active seasonal fronts and numerous beach nourishment events which added more than 1.8 million m^3 of sediment to beaches downdrift of the inlet. Coupling the two phenomena explains the spatiotemporal patterns of sediment texture within the placement area and downdrift.

The 2020 hurricane season, which contained seven named storms including TS Eta which impacted the area twice, primarily produced waves from the southeast throughout the season (Briggs et al., 2021). The impact of the wave events was evident on both sides of the Jupiter inlet with impoundment of sediment south of the inlet at R13A and erosion north of the inlet at R11. In addition, following the storm impact numerous beaches had ridge and runnel structures, a feature indicative of beach recovery after erosion (Wang and Briggs, 2015). Large storm-induced bathymetric changes included ridge migration at R24 and R27 resulting in significant volume changes at those locations. It’s worth noting that large migratory shifts of sediment ridges can influence wave dynamics and therefore morphologic change on the beach (although the temporal resolution and nourishment confined the scope of this study). Two of the surveyed beaches (R31 and R21) are updrift of a hard structure (pier and wave-exposed seawall, respectively) and experienced patterns of erosion unlike the other locations on open (i.e., non-structured) stretches of beach. The unnourished southern control location and northern locations that have not been nourished in a decade were also significantly impacted by the storms with slower post-storm recovery. It is likely that the 2020 hurricane season transported sediment north of the study area resulting in slow recovery periods (i.e., longshore processes first must reintroduce sediment to the system for accretion and recovery). These results emphasize the importance of sediment conservation within the system (i.e., no net loss in the sediment budget) for storm impact reduction and post-storm recovery.

Frequent nourishment events within the study area influenced beaches where sediment was placed and altered the bathymetry and sediment offshore in numerous locations during the equilibration process of initial scarp retreat followed by adjustments to a more natural beach slope (Elko and Wang, 2007; Roberts and Wang, 2012; Liu et al., 2019). Alterations to the bathymetry and sediment include more monotonic profiles and locations expected to have finer sediment in troughs contained coarser than expected sediment. The interruption of the littoral drift by the inlet results in a lack of sediment supplied to R13A and R15, therefore requiring frequent nourishment, with finer sediment most likely subsequently winnowed away towards the offshore during tidally induced flow currents (Wang et al., 2011). The impact of the inlet extends further south until the ebb-tidal delta connection occurs within the vicinity of R18 and R19 where sediment is added to the nearshore and downdrift beaches. The Juno Beach Pier and the wave-exposed seawall at the Jupiter Reef Club both alter longshore sediment transport and can create erosional hot spots.

Overall, nourished beaches were more resilient and predictable in their recovery to storms and wave events than non-nourished beaches, which is attributed to the influx of sediment from the projects. Results from this study suggest that non-nourished and non-managed beaches consider developing a management plan that would bolster their resilience by increasing the amount of sediment placed in the system, beach width, and in turn, provide more habitat and space for recreation. And if new management plans are put in to action for the non-managed beaches, monitoring of beach state and sediment are recommended to determine the general patterns of change to support longer-term best management strategies.

Conclusion

This study evaluated sediment characteristics and beach topo-bathymetry along 12 km of beach in Northern Palm Beach County, Florida (USA) over two years that included multiple high-energy wave and nourishment events. The study area was significantly impacted before each sampling event either by storms, nourishment, or both. Topo-bathymetric surveys and sediment samples that were collected were evaluated to better understand the primary controlling factors of the system. Over the course of the study 22 high-energy wave events and three nourishment events placing more than 1.8 million m^3 of sediment along the beaches altered the morphology. The primary controlling factors on the beach-nearshore physical environment include the structured Jupiter Inlet, offshore migrating sediment ridges, and high-energy wave events that move large amounts of sediment rapidly. More local factors include other structures such as the Juno Beach Pier and Jupiter Reef Club which cause changes to the sediment transport, frequently resulting in erosional hotspots. The frequent nourishment via BUDM placement adjacent to the inlet is necessary to combat erosion. The currently critically eroded and non-nourished beaches (FDEP, 2021) should be considered for nourishment as wave events lower their elevation and transport sediment out of the system resulting in slow post-storm recovery. Longer-term studies that can capture event and non-event changes are needed to support best management practices for this critically important ecosystem. Finally, non-nourished beaches should be considered for nourishment to improve resilience, but will require near-term monitoring to understand changes to the local morphodynamics and support long-term best-management practices.

CHAPTER 5: ENVIRONMENTAL INFLUENCES ON LOGGERHEAD SEA TURTLE NESTING, HATCHING, AND EMERGENCE SUCCESS

Introduction

Coastal erosion, occurring when sediment is removed from the beach, is a chronic issue along much of the shoreline in the United States. Beach nourishment is a common, nature-based solution that is utilized to combat erosion (Dean, 2002). However, it is important that the nourishment events do not, or have minimal, impacts on marine fauna resulting from changes in local beach morphology and sediment composition. This study evaluates anthropogenic and natural environmental influence on loggerhead sea turtle nesting, hatching, and emergence success.

Nesting sea turtles can be influenced by changes in beach and dune erosion or accretion (Roberts & Wang, 2012), high tide flooding (Witham, 1982), and seasonal disturbances such as hurricanes or tropical storms with high winds, waves, and inundation (Goldenberg *et al.*, 2001; Pike & Stiner, 2007; Webster *et al.*, 2005) leading to erosion and reduced habitat. Studies have shown that sea turtle nesting success (relative to false crawls), hatching, and emergence success are sensitive to environmental conditions, including beach slope and width, sand composition, temperature, grain size, and water potential (Milton *et al.*, 1997; Mortimer, 1990, 1995; Pike *et al.*, 2015; Wood & Bjorndal, 2000). Numerous studies have investigated the influence of beach nourishment slope and width, grain size, and sediment compaction on sea turtle nesting prior to the 2001 update of Florida (DEP) rules on sediment compatibility (Davis *et al.*, 1999; Ernest, 2001). Based on a comparison of sea turtle nesting success of a tilled and non-tilled nourishment project on Florida's east coast, Ernest (2001) found that immediate post-nourishment nesting success decline was unrelated to compaction and more likely related to the slope. Rumbold *et al.* (2001) also found that the principal effect of nourishment on sea turtle reproduction was a reduction in nesting success during the first year following project construction due to an overly steep beach profile or scarping. Beaches can take up to 12 months post-construction to fully reach profile equilibration (Willson *et al.*, 2017), which would coincide with nesting season. In addition, nourished beaches are constructed with wider, flatter berms to extend the width of the dry beach, which is associated with increased hatchling disorientation. One study reported a >600% increase in the number of disoriented hatchlings in the year following a renourishment event (Brock *et al.*, 2009). Steeper beaches with dark silhouettes encourage proper hatchling orientation towards the flat, brighter horizon of the ocean (Reintsma *et al.*, 2014; Tuxbury & Salmon, 2005), while flatter beach profiles increase the visibility of both skyglow and point sources of light that disorient hatchlings. Disoriented hatchlings are more prone to exhaustion, dehydration, and predation (Pankaew & Milton, 2018).

Sediment texture and composition in nourished areas and downdrift beaches can also impact the nesting preferences of turtles (Mortimer, 1990, 1995). Mortimer (1990) analyzed the influence of sediment characteristics on nesting behavior and clutch success and found that beaches with coarse, dry sediment caused females to have difficulty digging chambers resulting in multiple false crawls. Mortimer (1995) also examined factors affecting beach selection of loggerhead turtles using a multiple regression approach where variables such as sand softness, beach length, and height, were found to be important effects in nest-site selection.

The objectives of this paper are to identify the potential impacts of morphology and sediment variability on the reproductive success of loggerhead sea turtles using a combination of physical and biological data. Specifically, this study examines the effects of time of year a turtle nests, nourishment status, beach width, slope, and sediment sorting on loggerhead nesting, hatching, and emergence success on the southeast Florida beaches that host tens of thousands of endangered loggerhead turtles each year (LMC, 2020). Beaches in Palm Beach County (PBC), Florida are exposed to frequent events that can cause significant morphologic and sedimentologic changes such as winter cold fronts, beach nourishment projects, and frequent tropical storms (Briggs *et al.*, 2021). There have been large contributions to the body of knowledge and high importance placed on the biological impacts of sea turtle reproductive success, however, there has been limited evaluation from a geologic perspective. A better understanding is needed for evaluating thresholds of sediment texture and morphologic variability of regional beaches and the impact on the beach as a habitat. Results of this study identify significant environmental impacts on loggerhead sea turtle nesting success. Continued improvements in coastal management strategies, specifically from nourishment, will minimize impacts on marine turtles and promote balance between the built and natural environment.

Methods

Study Area

The study area is in northern PBC, Florida, USA. The beaches consist of a mix of clastic and carbonate is moderately sorted to moderately well sorted medium sand

(Brown & Briggs, 2020; Chapter 3), have undergone numerous beach nourishment projects, and are subject to numerous coastal forces that all contribute to sediment transport, often away from the beach (Chapter 3). The study area contains a mix of managed open coast beaches that receive periodic nourishments (between R-monument R-13 and R-34) and non-managed open coast beaches that do not receive any nourishment (R-03-R11 and R41; Figure 5.1; FDEP, 2021). Across the microtidal, wave-dominated study area, one of several structured tidal inlets of south Florida, the Jupiter Inlet, interrupts the net southward longshore sediment transport. The volumetrically small ebb-tidal deltas are asymmetrically skewed to the south (Stauble, 1993).

Figure 5.1 Study area map of northern Palm Beach County, Florida with labeled locations used and beaches with management identified.

Three species of sea turtles nest along the east coast of Florida, including leatherback, green, and loggerhead sea turtles. The Northwest Atlantic Ocean's loggerhead nesting population is the largest in the world (Casale & Tucker, 2015) and of this population, 90% of the aggregation nest in Florida (Ceriani & Maylan, 2015). Furthermore, PBC beaches account for approximately 25% of loggerhead sea turtle nests laid in Florida and are one of the most important rookeries in the world (Loggerhead Marinelife Center, 2020). More than 10,000 loggerhead nests are recorded each year in PBC, with an average of 12,448 nests each year (Table 1). Typical, or expected, nesting success is 1 laid nest for every 1 false crawl (or a nesting success rate of 50%). Over the last six years, loggerhead nesting success has averaged 47.5%. Understanding environmental impacts on reproductive success are important because while loggerheads do nest in PBC in high abundance, they are frequently listed as threatened or endangered.

Table 5.1 Loggerhead nests and false crawl data (Loggerhead Marinelife Center, 2016-2022)

Year	Loggerhead Nests	False Crawls
2016	15234	38859
2017	11180	--
2018	10977	25507
2019	13400	22444
2020	13059	22488
2021	10836	28738

Beach nourishment is frequent in northern PBC, with three nourishment events during this two-year study (FDEP, 2021). The inlet adjacent Jupiter Beach Park and Carlin Park receive BUDM placement when the inlet is dredged on a near-annual basis. In 2020, 451,924 m^3 of sediment was placed from R13.5-R19 from an offshore borrow area as part of the North County Comprehensive Shoreline Protection Project (PBC-ERM, 2021a). Further south of the Jupiter Inlet from R26-R38, 917,465 m^3 of sediment was placed from an offshore borrow (PBC-ERM, 2021b). Also, in 2021,162,085 m^3 (99,392 m^3 inlet sand trap, 68,809 m^3 Atlantic interior waterway, AIWW) of sediment was placed between ~R14 and R17 (PBC-ERM, 2021a).

Between 2020-2021, 22 wave events impacted the study area including seven named tropical storms of varying intensity and proximity to the study area. In 2020 there were 15 events and in 2021 there were 7. The energetic wave events were categorized based on sustained max wave height of at least 2.25 m. In 2020 there were five late winter and early spring storms in addition to tropical storms Bertha, Isaias, Sally, Teddy, Epsilon, and Eta, followed by two post-hurricane season wave events. In 2021 there were four wave events in late winter and spring before tropical storm Anna and two subsequent fall wave events.

Date Collection

Loggerheads nest in larger quantities than the two other turtle species in the study area. In addition, they utilize the full extent of the beach for their nest site selection (compared to more limited nesting preference locations of the leatherback and green sea turtles). Because of their ecological importance and endangered status, loggerheads have been the subject of multiple studies in South Florida to improve conservation efforts

(Cisneros *et al.*, 2017; Reintsma *et al.*, 2014; Rumbold *et al.*, 2001; Salmon, 2003; Stewart & Wyneken, 2004; Tuxbury & Salmon, 2005).

15 locations (5 north and 10 south) north and south of the Jupiter Inlet were selected to evaluate nourished and non-nourished beach conditions. Subaerial data collection of morphology and sediment occurred in the spring and fall of 2020 and 2021. Real-Time Kinematic Global Positioning System (RTK-GPS) was used to collect morphological information from the seaward side of the dune to the swash zone. Sediment from the mid-beach was collected at each location during all four events. Mid-beach sediment was used as a representative sample because loggerhead sea turtles frequently use the full extent of the beach. Sediment was analyzed for grain size distribution and bulk statistics (e.g., mean grain size and sediment sorting) following FDEP protocol and applicable sections of ASTM. Grain size distribution and statistics are determined from sediment analysis at half- and quarter-phi sieve intervals between -4 (16 mm) and 4φ (63 μm) using a Ro-Tap Sediment Shaker.

Data on sea turtle nesting, hatch, and emergence success, nest washout, predation, and disorientation were obtained from Loggerhead Marinelife Center (LMC) which uses state-permitted nesting surveyors or data from the Florida Fish and Wildlife Conservation Commission Fish and Wildlife Research Institute (FWC), which houses all relevant statistical data on sea turtle nesting in Florida. By state requirement, sea turtle monitoring and nest identification is only a fraction of the total nests (Table 5.2). Nests that were washed out, predated, or lost were removed from the dataset before analyzing nest events. Nesting events are defined as where nesting was attempted and resulted in either a nest or false crawl.

Table 5.2 Loggerhead nesting events and marked nests by location for 2020 and 2021

Location	2020 Nesting Events	2020 Successful Nests	2021 Nesting Events	2021 Successful Nests	2020 Marked Nests	2021 Marked Nests
R03	1313	491	1297	525	11	9
R05	690	258	294	120	7	1
R07	991	347	826	281	7	8
R09	1497	566	1167	475	9	9
R11	864	306	567	202	3	7
R13	230	47	170	34	7	3
R15	949	342	429	83	10	5
R18	394	136	483	182	8	10
R19	350	127	304	179	18	26
R21	183	80	365	117	18	21
R24	469	266	378	158	3	5
R27	333	151	241	75	1	2
R31	153	52	181	48	2	0
R34	506	116	374	110	4	2
R41	536	175	579	179	1	5
Total	9458	3460	7655	2768	109	113

Nesting success (Equation a), hatching success (Equation b), and emergence success of loggerhead sea turtles (equation c) were calculated from the raw marine turtle data provided using equations from Miller (1999).

$$Nesting\ Success\ (\%) = \frac{Number\ of Nests}{Total\ Crawls}\, x\ 100 \qquad \text{Equation 5.1}$$

$$Hatching\ Success\ (\%) = \frac{Number\ of\ Empty\ Shells}{Total\ Eggs\ in\ the\ Nest}\, x\ 100 \qquad \text{Equation 5.2}$$

$$Emergence\ Success\ (\%) =$$

$$\frac{Number\ of\ empty\ shells - (Number\ of\ Live + Number\ of\ Dead)}{Total\ Eggs\ in\ the\ Nest}\ x\ 100 \qquad \text{Equation 5.3}$$

Only nests within a 150 m radius of the surveyed transects were evaluated in this study (i.e., to ensure environmental conditions of the nests selected are represented by the physical attributes of the site locations surveyed and sampled).

Statistical Analyses

All probability values (p-values or p) were evaluated to α = .05. Spatial autocorrelation (Global Moran's I) was examined for the nesting, hatching, and emergence success to better understand the distribution of the data. Global Moran's I returns a probability and z-statistic that indicates spatial clustering with a positive z-score indicating the dataset is more spatially clustered than expected if the underlying processes were random and negative indicating the dataset is more dispersed. The differences in nesting variables (nesting, hatching, and emergence success) were analyzed for statistical significance in JMP 16 using mixed-effects models and the main effects included: date, location, nourishment status, beach width, slope, and sediment sorting to account for all measured physical impacts. Date was separated into four categories so nests could be divided among the four sampling periods for physical environment conditions. The dates of sampling were spring 2020, fall 2020, spring 2021, and fall 2021. Turtle nesting, hatching, and emergence were split at the middle date for each year of the data set. 15 locations were surveyed and turtles were assigned to the nearest transect if they were within a 150 m radius. Nourishment status was classified as nourished within the past 12 months or not to examine if recent nourishment impacted the turtle's reproductive success. Beach width was split into five categories: 0-20 m, 20-40 m, 40-60 m, 60-80 m, and 80+ m. Slope was split into four categories: 1:1-1:5, 1:6-1:10, 1:11-1:15, and 1:16+. Finally, sediment sorting is determined through the sediment grain size analysis and represents the standard deviation value of the grains.

Nesting success was examined using a mixed model with date, location, nourishment status, beach width, slope, and sediment sorting as main effects. Hatching success was examined using a mixed model with date, location, nourishment status, beach width, slope, and sediment sorting as main effects. Emergence success was examined using a mixed model with date, location, nourishment status, beach width, slope, and sediment sorting as main effects. Post-hoc differences were determined using Tukey's tests for hatching and emergence. A summary of variables is provided in Table 5.3.

Table 5.3 Summary of variables used in mixed models.

Variables	
Nesting attributes	Nesting success
	Hatching success
	Emergence success
Beach attributes	Location
	Width
	Nourishment status
	Slope
	Sediment sorting
Time attributes	Sampling event

Results

Reproductive Success

Throughout the two-year study period, there were a total of 17,113 nesting events where a loggerhead emerged on the beach within the 150 m radius of the surveyed transects, with 9,458 events in 2020 and 7,655 in 2021 (Table 5.3). Of the total events, 9,506 were north of the inlet at five of the locations and the remaining 7,607 were south of the inlet at the other ten locations (Table 5.2). 13,008 events occurred on non-nourished beaches while 4,105 were on recently nourished beaches.

Nesting events were most commonly attempted on beaches with widths between 20 and 40 m and slopes ranging from 1:6 to 1:10. On nourished beaches, nesting events occurred most frequently on beaches between 40-60 m in width and on non-nourished beaches between 20-40 m. Overall, loggerhead sea turtle nesting success varied between 20% to 59% throughout the two years. While an inverse relationship was found between beach width and nesting attempts, higher hatch and emergence success was found on wider beaches. Average nesting success was lower at wider beaches such as R13 and R15 than narrow beaches such as R03 and R05 with a 49% success (n = 419). Beaches with widths of 20-40 m had a 39% success, 40-60 m had a 34% success, and 60-80 m also had 34% success (n = >2,500 for all). The widest beaches of >80 m had a 25% success rate (n =217). The average hatching and emergence success increased with beach width except for on beaches between 0-20 m which had 95% hatching and 94% (n = 2) emergence success. At beaches between 20-40 m, the hatching and emergence success were 65 and 62% (n = 51), at 40-60 m they increased to 73 and 70% (n = 101), and at 60-80 m there was a further increase to 77 and 72% (n = 68).

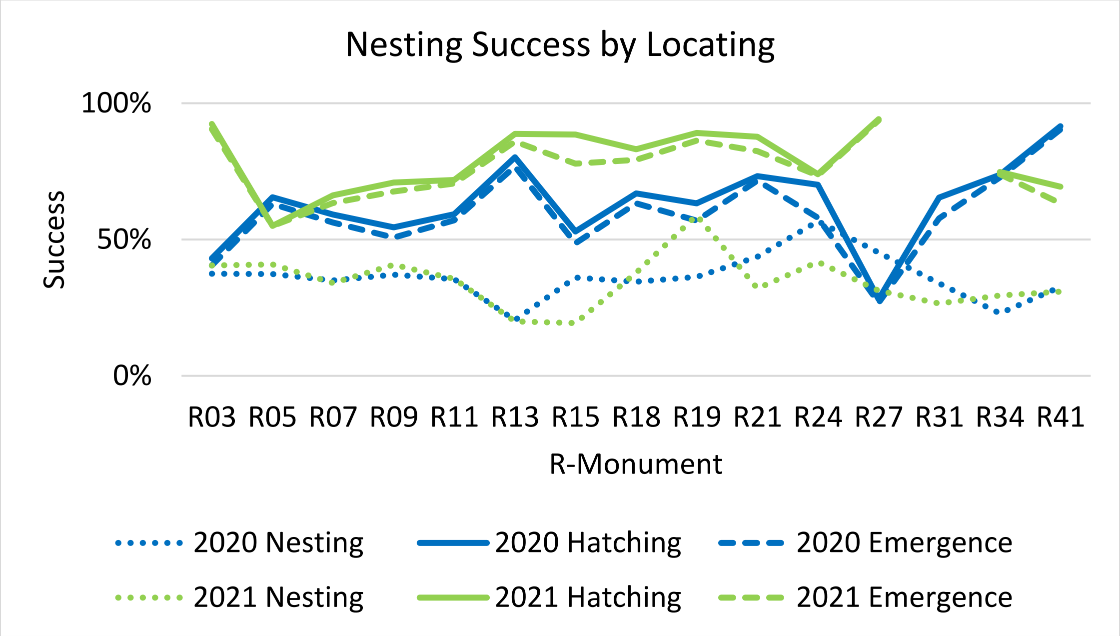

Figure 5.2 Sea turtle reproductive success percentage including nesting, hatching, and emergence plotted by location.

North of the inlet, nesting success either remained similar or slightly increased between 2020 and 2021. The highest nesting success measured was 37% measured at several locations in 2020 and 41% at R05 and R09 in 2021. However, both are below the desired threshold of a 50% nesting success. North of the inlet, hatching success ranged from 43% at R03 to 66% at R05 in 2020 and increased to a range of 55% at R05 to 92% at R03 in 2021 (Figure 5.2). Except for the 43% success rate at R03 in 2020, most hatching success values were approaching or exceeding the generally desired 60% hatching success rate for loggerhead sea turtles (Bladow, 2017). In addition, the emergence success rate north of the inlet was close to the hatching success rate ranging from 40% to 91% at R03 in 2020 and 55 to 63% at R05 in 2021. Therefore, despite lower nesting success rates, when the loggerheads did nest, their hatch and emergence success outcomes were generally positive.

Immediately south of the inlet at R13, nesting success was the lowest measured throughout the study area with a 20% success rate n = 277. Hatching success at this location was 80 and 89% with a 77 and 86% emergence success in 2020 and 2021, respectively. Overall, although this area is not generally thought to be conducive to nesting, the nests that were laid here had a positive outcome.

From R15 to R34 (mixed management beaches), no location had >50% nesting success of loggerheads for both years. The nesting success rate in 2020 ranged between 23% at R34 and 57% at R24 and between 19% at R15 to 59% at R19. A very low hatching and emergence success of 28% and 27%, respectively, were measured at R27 during the 2020 nesting season. While nesting success at R27 was among the highest in 2020 at 45%, it is only based on one nest within the vicinity in 2020. Hatching and emergence success of 53 and 49%, respectively, were also measured at R15 in 2020. However, the other locations had between 63% to 92% hatching success with 57 to 90% emergence success in 2020. In 2021, hatching and emergence success were higher than in 2020 with between 75 and 94% and 73 to 94%, respectively, across the managed beaches of R15 to R34. No nests were available for analysis at R31 due to either predation or washout. Overall, while nesting success varied between 2020 to 2021, most of the hatching and emergence success exceeded the 60% threshold.

The control beach at R41 had nesting success of 33 and 31% in 2020 and 2021, respectively. Despite the low nesting success, in 2020 the hatching success was 92% with a 90% emergence success. In 2021, the hatching success was reduced to 69% with an emergence success of 63%. Again, although the nesting success is not as relatively high, for those that do nest, the hatching and emergence success meets the desired threshold of 60%.

In summary, although nesting success rarely exceeded the 50% desired threshold, the hatching and emergence success generally achieved the desired threshold of 60%. Overall, hatching and emergence success increase between 2020 and 2021, with only a few exceptions. After the nourishment projects, the managed beaches also generally high higher hatch and emergence success than those north of the inlet or at the control beach (except at R03 with very high success values).

Statistical Analysis

The turtle nesting, hatching, and emergence data was tested for spatial autocorrelation to better understand spatial trends and independence of residuals. Global Moran's I statistical analysis resulted in a failure to reject the null hypothesis for hatching (p=.0844) and emergence success (p=.2301) as the observed spatial pattern of hatching and emergence success could be random. For nesting (p=.0000) the null hypothesis was rejected, and the z-score was positive which suggests the spatial distribution of nesting locations was more spatially clustered than would be expected if underlying spatial processes were random.

Nesting success was evaluated using the chi-square test of independence to examine the effect of date, location, nourishment status, beach width, slope, and sediment sorting on nesting success. The relationship between nesting success and date X^2, (3, N=17113) = 287.3483, p=<.0001, location X^2, (14, N=17113) = 112.1531, p=<.0001, beach width X^2, (4, N=17113) = 18.2602, p=<.0011, and sediment sorting X^2, (1, N=17113) = 21.5922, p=<.0001 were significant. Nourishment status and slope were not significant effects. Higher loggerhead nesting was based on location, date, beach width, and sediment sorting. Locations that were most likely to have turtles nest instead of false crawl included all managed beaches and one non-managed location north of the inlet. More successful beaches were R21 and R27 in 2020 and R05 and R19 in 2021. R24 was the only beach to be likely to have more success in both years. The beaches that were most likely to have nesting attempts fail were R15 and R31 in 2021, and R13 and R34 in both years.

Loggerhead sea turtle hatching was statistically significant in a mixed model ANOVA (Analysis of Variance) F(25, 196) = 3.9843; p<.0001 using nesting date, location, nourishment status, beach width, slope, and sediment sorting as main effects. Nesting date was the only significant effect on hatching F (3, 196) = 17.1956, p<.0001. Tukey's HSD test for multiple comparisons found that date was similar and successful for hatching when turtles nested in both the spring and fall of 2021 (Figure 5.3). Furthermore, the least successful hatching period was in fall 2020 which coincided with the intense tropical storm season (Briggs *et al.*, 2021).

Loggerhead sea turtle emergence success was significant in a mixed model ANOVA F(25,196)=3.2880; F<.0001 using nesting date F (3, 196) = 14.5972; 0<.0001), location, nourishment status, beach width, slope, and sediment sorting as main effects. Nesting date was the only significant effect on emergence. Like hatching success Tukey's HSD test for multiple comparisons found that date was similar and successful for hatching when turtles nested in both the spring and fall of 2021 (Figure 5.4). The least successful emergence period was in fall 2020 which coincided with the intense tropical storm season (Briggs *et al.*, 2021).

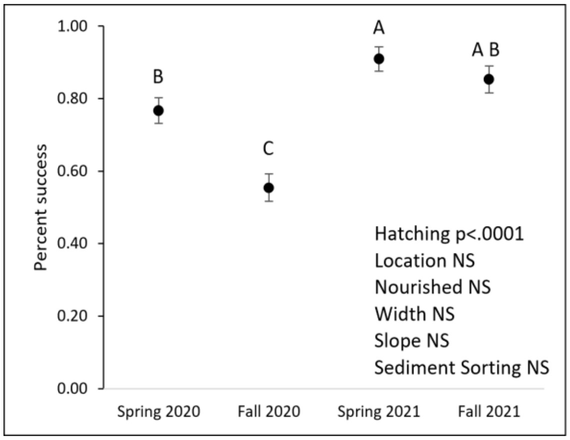

Figure 5.3 . Percent of hatching success vs date. Percent varied in whole model statistics and date was the only significant effect. Error bars indicate ± standard error differences. Post hoc statistical differences among groups are denoted with differing letters above each. Similar letters mean groups were alike.

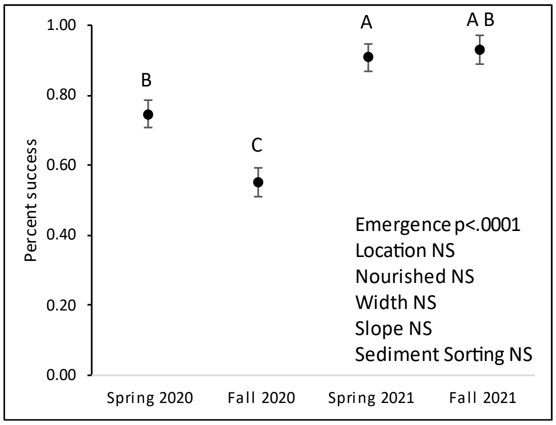

Figure 5.3 Percent of emergence success vs date. Percent varied in whole model statistics and date was the only significant effect. Error bars indicate ± standard error differences. Post hoc statistical differences among groups are denoted with differing letters above each. Similar letters mean groups were alike.

Discussion

Loggerhead hatching and emergence success on the beaches exceeded 60% in both 2020 and 2021, however, the nesting success was below 50% in both 2020 and 2021 (by upwards of 15% lower). The managed beaches generally outperformed the non-managed northern and “control” beaches in hatching and emergence success while containing a similar number of eggs in each nest. Of the managed beaches, R13, R18, and R21 were above the average of all the beaches for both 2020 and 2021 in hatching and emergence success. Although the hatching and emergence success was higher on wider beaches, no statistically significant correlation was found.

In nesting, the timing, location, beach width, and sediment sorting were all identified as significant. Nesting sea turtles had more success on beaches that are managed than those that are non-managed. The overall width of the managed beaches is greater than the non-managed at nearly every location which was beneficial for turtle nesting success. However, the reason the sea turtles choose specific beaches is still unclear. Some studies suggest nest-site selection is through random selection relative to beach and dune features (Eckert, 1987; Hays et al., 1995; Witherington et al., 2011). Other hypotheses have been supported with correlative evidence for micro-habitat cues are used by turtles to select nesting sites. Signals potentially used by the turtles include temperature (Stoneburner and Richardson, 1981), the height of dunes or barrier features such as sea walls (Camhi, 1993; Witherington et al., 2011), and slope (Provancha and Ehrhart, 1987; Wood and Bjorndal, 2000). In addition to many managed beaches having high reproductive success rates, the northern beaches that are non-managed had consistently high nesting success and at R03 and R05 specifically, there was high hatching and emergence success.

The largest factor in both hatching and emergence success as identified through mixed model ANOVAs was the timing when nesting occurred (between the four dates) within the nesting season. Both the hatching and emergence were more likely to succeed in both the spring and fall 2021 intervals. In 2021, the overall beach change and the number of high-energy wave events were less than in 2020 (Chapter 4). The least likely period of nesting for success in hatching and emergence was in the fall of 2020 which coincided with the latter portion of the most active Atlantic hurricane season on record (NOAA, 2022). This active wave period brought about rapid beach change including both erosional features such as scarps and recovery features such as ridge and runnels (Wang and Briggs, 2015; Briggs et al., 2021; Chapter 4). The resultant morphology change altered the beach environment (removing or adding sediment), likely impacting hatching and emergence success. In stormy years it has been observed that nearly 100% of nests failed in areas of the beach that were destroyed or largely eroded (Witherington, 2011).

Impacts observed in the statistical models and the standard reproductive success information suggest that both natural and anthropogenic impacts affected the turtles. While natural impacts cannot be controlled (intense wave events and active storm seasons), anthropogenic activities can be minimized to protect the endangered species. Future research on the physical environment and its impacts on nesting sea turtles should include more frequent surveys of the beach morphology that may better quantify when changes occur leading to impacts on reproductive success. Along with a finer temporal scale, surveying the nearshore variable bar and trough morphology may aid in better understanding nest site selection. An increase in the balance of successful nests surveyed would also provide more a robust analysis for each location that would aid in statistical confidence of anthropogenic and natural impacts. Furthermore, for sea turtle conservation the number of eggs in each nest chamber that succeed is important and also could be used to better understand the impacts of the various reproductive statistics. Future research is needed that uses a thorough surveying method to aid in the understanding of the number of turtles that emerge from the nest and ultimately reach the sea. Witherington et al. (2011) performed a similar analysis on loggerhead nesting and marked every nest within their study area which provided strong confidence in their analysis across the study area. The methods employed resulted in a better understanding of geological impacts on nesting behavior, however, the combination of more surveys and successful nests being marked likely would likely yield even better insights into the impacts of both natural and anthropogenic influences on nesting behavioral changes within the area.

Conclusion

The beach serves as critical habitat for endangered nesting sea turtles and is therefore imperative to continuously evaluate how natural and anthropogenic activities may be altering physical properties. Despite lower than desired nesting success recorded throughout the study area, higher hatching and emergence success occurred during the post-2021 nourishment season. While nesting success was below average on the heavily managed inlet adjacent beaches, hatching and emergence success were higher. Despite the overall decline in nests from 2020 to 2021, the nests that were laid had better outcomes in their hatching and emergence success. In addition, although sediment and morphology including beach width and slope varied, no statistically significant beach characteristics adversely impacted the overall reproductive success metrics of the loggerhead sea turtles. The largest influence on the nesting, hatching, and emergence appears to be due to the active storm season of 2020 (NOAA, 2022). This intense storm activity strongly indicates the need for further analysis to better understand the physical properties of the beach environment under less extreme and more common conditions, especially given climate change predictions of more intense storms in the future. In summary, the current environmental thresholds in place for beach nourishment projects did not adversely impact the hatching and emergence success of loggerhead sea turtles during the two-year study but instead suggest that these practices are providing suitable habitat to support reproductive success and conservation efforts.

CHAPTER 6: THE EFFECT OF BEACH NOURISHMENT ON NEARSHORE WATER QUALITY AND HABITAT

Introduction

Nearshore turbidity along high-energy beaches is common, caused by high-density suspended individual particles from natural events such as river discharge, phytoplankton, and wave events, or anthropogenic activities such as beach nourishment (Angino & O'Brien, 1968; USACE, 1989; Speybroeck *et al.*, 2006). In South Florida, beach nourishment is a common solution to replenish sediment eroded from the beach. Specifically, in northern Palm Beach County (PBC), FL, nourishment events occur on a near-annual basis using beneficial use of dredged material from the Jupiter Inlet (National Beach Nourishment Database, 2022). Turbid water along beaches are not generally a significant concern as they disappear rapidly as fine particles are moved further offshore (Naqvi & Pullen, 1982; Speybroeck *et al.*, 2006; USACE, 1989; Van Dolah *et al.*, 1992). However, turbidity in some locations can last for extended periods (Goldberg, 1989; Hurme & Pullen, 1988; Manning *et al.*, 2013).

While turbidity is a natural phenomenon, prolonged turbidity can indirectly influence numerous animals and plants in the nearshore (Greene, 2002; USACE, 1989). In South Florida, thousands of migrating blacktip sharks overwinter in large aggregations in the nearshore waters each year (Figure 6.1; Kajiura & Tellman, 2016). The blacktip sharks are commonly found in northern Palm Beach County (PBC), Florida, USA, and aerial flights are regularly used to quantify their location and abundance during their migration from January to April (Kajiura & Tellman, 2016). However, the annual blacktip migration coincides with the beach nourishment period of November to March, which creates the potential for turbidity to affect the species in the nearshore. The objectives of this study are to quantify both the abundance of blacktip sharks in the study area and the spatiotemporal extents of turbidity that may impact their behavior in the nearshore.

Figure 6.1 Blacktip shark aggregation south of the study area captured during an aerial survey. The plane tire (on left) truncates the visual on a group of blacktip sharks.

The influence of nourishment-induced turbidity on nearshore fauna is limited as studies are generally conducted as target studies or applied generic turbidity research (Greene, 2002), likely due to the short duration of sediment suspension (Burlas *et al.*, 2001; Naqvi & Pullen, 1982; Speybroeck *et al.*, 2006; USACE, 1989). However, some studies have found turbidity to be a persistent problem, reducing visibility post-construction for longer periods (e.g., 7 years; Goldberg, 1989; Hurme & Pullen, 1988; Manning *et al.*, 2013). Manning *et al.* (2013) found elevated turbidity 4-8 months after construction where waves agitated previously buried fine sediment. Because turbidity is a natural event, nearshore biological communities have a natural resilience toward short-term shifts in turbidity (Van Dolah *et al.*, 1994; Burlas *et al.*, 2001; USACE, 2002). Therefore, human-induced turbidity resulting from most beach restoration projects are not expected to significantly impact marine organisms (Burlas *et al.*, 2001; Greene, 2002; Speybroeck *et al.*, 2006; USACE, 1989, 2002; Van Dolah *et al.*, 1994). Additionally, some studies suggest that turbidity offers protection for nearshore fish in an open environment, reducing visibility for visual predators such as fish, crabs, and birds (Beyst *et al.*, 2002; Essink, 1999; Nelson, 1985; Speybroeck *et al.*, 2006; USACE, 1989) which is potentially both beneficial and detrimental to the blacktip sharks as visual mesopredators (Compagno, 1984; Castro, 2010). Ultimately, beach nourishment is increasing in frequency (Elko *et al.*, 2021) and little research has been conducted on the impacts of continuous or repeated turbidity (Greene, 2002; SAFMC, 1998) and it has been suggested that repeated nourishment can initiate long-term elevated turbidity (Greene, 2002; Speybroeck *et al.*, 2006).

Greene (2002) related the severity of sediment resuspension to several factors including wave energy, amount of sediment placed on the beach, quality of the sediment, and mode of placement. The method of placing sediment on a beach for nourishment can also influence the degree of turbidity(Burlas *et al.*, 2001; Kana & Mohan, 1998; USACE, 1989). Kana and Mohan (1998) found that sediment supplied via pipelines, a commonly used method, allows for coarser material to settle near the backshore deposit bank and finer material is deposited downslope with the slurry. This method improves the lifespan of the project, however, the fines that wash into swash can cause elevated turbidity (Burlas *et al.*, 2001; Kana & Mohan, 1998). Equipment such as silt curtains are available for deployment to reduce turbidity if sensitive organisms or habitats are present, however, they are not generally deployable in high-energy environments (USACE, 1989).

The blacktip sharks that are commonly found in the shallow, warm waters immediately offshore in PBC (Castro, 2010; Kajiura & Tellman, 2016) are cosmopolitan, vagile, mesopredator in tropical and warm temperate waters globally (Compagno, 1984). In the United States, the blacktips range is from New England to the Florida Keys, and the Gulf of Mexico, however, the primary range which is temperature driven is from North Carolina to southeastern Florida (Castro, 2010; Kajiura & Tellman, 2016; Schlaff *et al.*, 2014). Because of the generally clear water and light-colored sandy seafloor, the sharks are easily and frequently observed from the air (Kajiura & Tellman, 2016).

This study will examine the potential impacts nourishment-induced turbidity has on annual blacktip shark aggregations and behavior with the goal of better understanding the cause, extent, duration, intensity, and impacts of the turbidity along with impacts on the location of blacktip sharks in the nearshore. The objectives of the study are to quantify the blacktip shark abundance and evaluate nourishment caused turbidity plumes south of the Jupiter Inlet over 24-months from 2020 to 2021.

Methods

Study Area

Northern Palm Beach County, Florida, USA is a microtidal, wave-dominated coast. The beaches consist of a mix of clastic and carbonate is moderately sorted to moderately well sorted medium sand (Brown & Briggs, 2020). The general morphology within 100 m of the shore within the study area generally consists of frequent bar and trough morphology, contained migratory ridges, or consisted of some exposed hard bottom along with sediment that varies most frequently from medium to fine sand with less frequent areas of coarse sand (Brown & Briggs, 2022). One of several structured tidal inlets of south Florida, the Jupiter Inlet, interrupts the net southward longshore sediment transport. The volumetrically small ebb-tidal deltas are asymmetrically skewed to the south (Stauble, 1993). The Jupiter Inlet is a navigational inlet that provides access to the Atlantic Intracoastal Waterway along with being an outlet for the Loxahatchee River.

The study area contains a mix of managed open coast beaches that receive periodic nourishments (between R-monument R-13 and R-38) and non-managed open coast beaches that do not receive any nourishment (R-39-R-60; Figure 6.2; FDEP, 2020). The northern extent of turbidity plumes was the Jupiter Inlet’s south jetty and extended south toward John D. MacArthur Beach State Park, but rarely did turbidity impact the nearshore of the Park. The aerial flights that were conducted were larger than the study area, however, only fight records from within the study area were used. Northern PBC has near-annual beach nourishment projects using inlet dredged sediment as well as larger shore protection projects constructed using an offshore sediment source. Three nourishment events took place during this two-year study (FDEP, 2021). The inlet adjacent Jupiter Beach Park and Carlin Park receive BUDM placement when the inlet is dredged on a near-annual basis. In 2020, 451,924 m^3 of sediment was placed from R13.5-R19 from an offshore borrow area as part of the North County Comprehensive Shoreline

Protection Project (PBC-ERM, 2021a). Further south of the Jupiter Inlet from R26-R38, 917,465 m^3 of sediment was placed from an offshore borrow (PBC-ERM, 2021b). Also in 2021,162,085 m^3 (99,392 m^3 inlet sand trap, 68,809 m^3 Atlantic interior waterway, AIWW) of sediment was placed between ~R14 and R17 (PBC-ERM, 2021a).

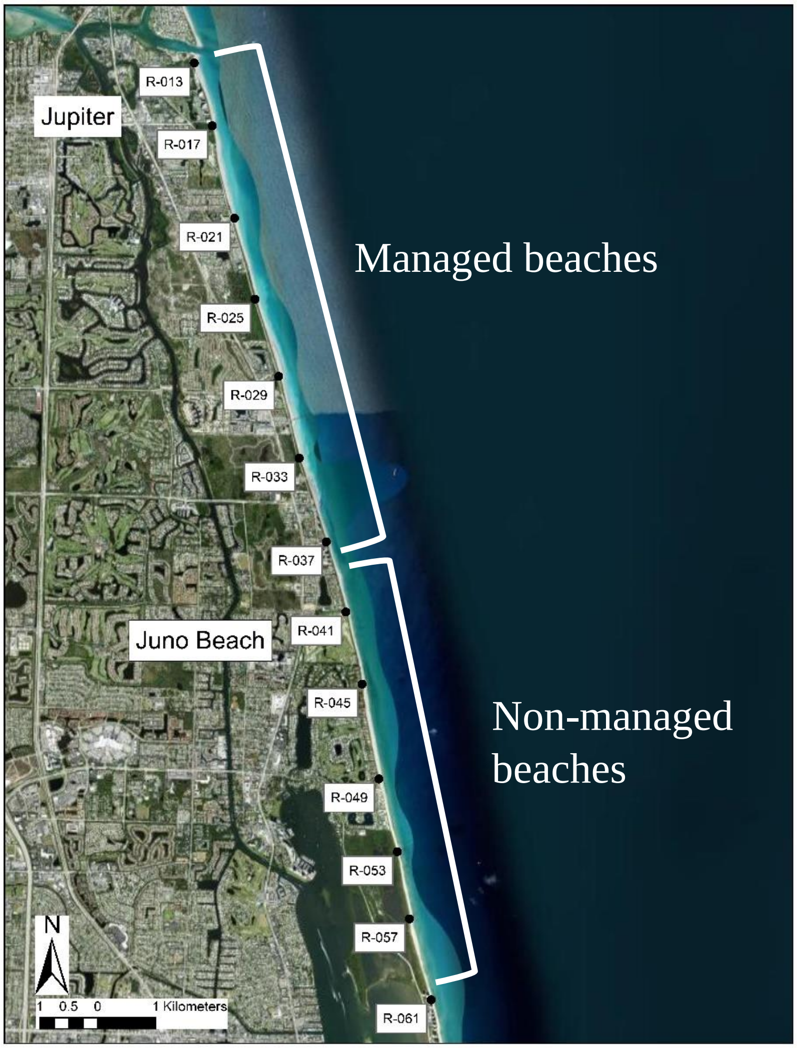

Figure 6.2 Study area south of the Jupiter Inlet containing both nourished and non-nourished beaches.

Data Collection

Between 2020 and 2021 aerial survey flights were completed monthly to capture photos and video of the nearshore between the Palm Beach Inlet and Jupiter Inlet using a Cessna 172 aircraft flown at approximately 150 m altitude and approximately 150 km h^{-1} airspeed. This combination of altitude and airspeed provides adequate image resolution. Survey flights were conducted only on days in which the wind speed and direction produced relatively calm sea surface conditions which facilitated viewing into the water. Flights were flown in the mornings between 0800–1100 local time, which provided optimal lighting with minimal surface glare. The planned flight path is from south to north and is flown so images capture from the shoreline to ~250 m offshore (Figure flight image). Onboard there are two mounted cameras, one HD video camera and a DSLR with a polarizing filter and GPS (Figure 6.3). The video records continuously and the camera is set to shutter every two seconds which captures the entire study area.

Underwater block cameras were deployed in the southern end of the study area within the Park boundaries to observe the sharks' cross-shore location in an area often less impacted by anthropogenic activities (boating, swimming, surfing,). The block camera consists of a small concrete slab, steel pole, and camera mounted to the pole (Figure 6.4). These cameras are deployed cross shore at 50 m, 100 m, 150 m, and 200 m from mean high tide. The camera record continuously for 90 minutes and footage is analyzed to quantify shark and fish species abundance (not including blacktips) at each camera location.

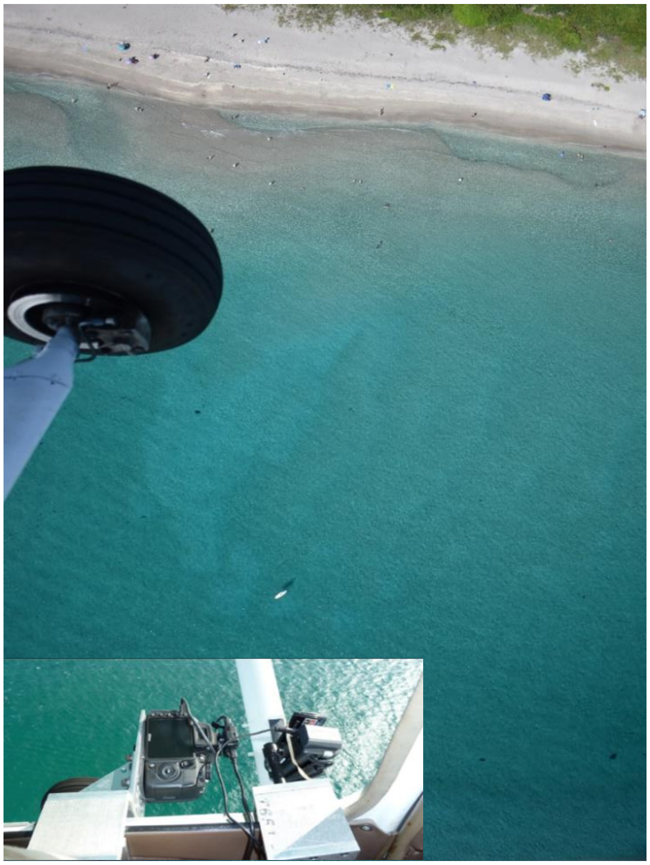

Figure 6.3 Image of typical view of nearshore environment from the survey plane and image of DSLR camera (left) and HD video camera (right).

Figure 6.4 Left image is a student deploying a block camera. Right image is a screen shot of a blacktip shark swimming past a deployed block camera.

Data Analysis

More than 10,000 images were analyzed for water clarity. When turbidity in the nearshore was found, attributes were noted about the plumes including extent where the start location and end location were associated with a coastal range monument, cross-shore extent (meters), and intensity recorded on an ordinal scale from 1-5 with 1 being low turbidity and 5 being most intense turbidity (Figure 6.5). Turbidity score determinations were intended to represent the intensity of the plumes. A score of 1 would exhibit a slight cloudiness in the water where the bottom would be largely visible and hard bottom or color contrasted features would still stand out. 2 would be less visibility or cloudiness in smaller plumes where it is challenging to identify hardbottom or other features. A score of 3 would be given when no features could be identified or containing areas where currents create clearer patches (Figure 6.5, C). Scores of turbidities at 4 and 5 both contain consistent clouds of intense turbidity, however, a score of 5 is given when the turbidity does now allow for any visual in the water and often there are white plumes found within the larger off-white plumes. Surveys that had no turbidity were scored a 0. The turbidity plume information was evaluated in ArcGIS to determine the measured length and approximate area of the plume. River turbidity identified by its brown color in contrast to the milky sediment turbidity was quantified separately in all events. When the brown-colored river water was within the study area along with the off-white turbidity normally seen, the turbidity was assessed separately.

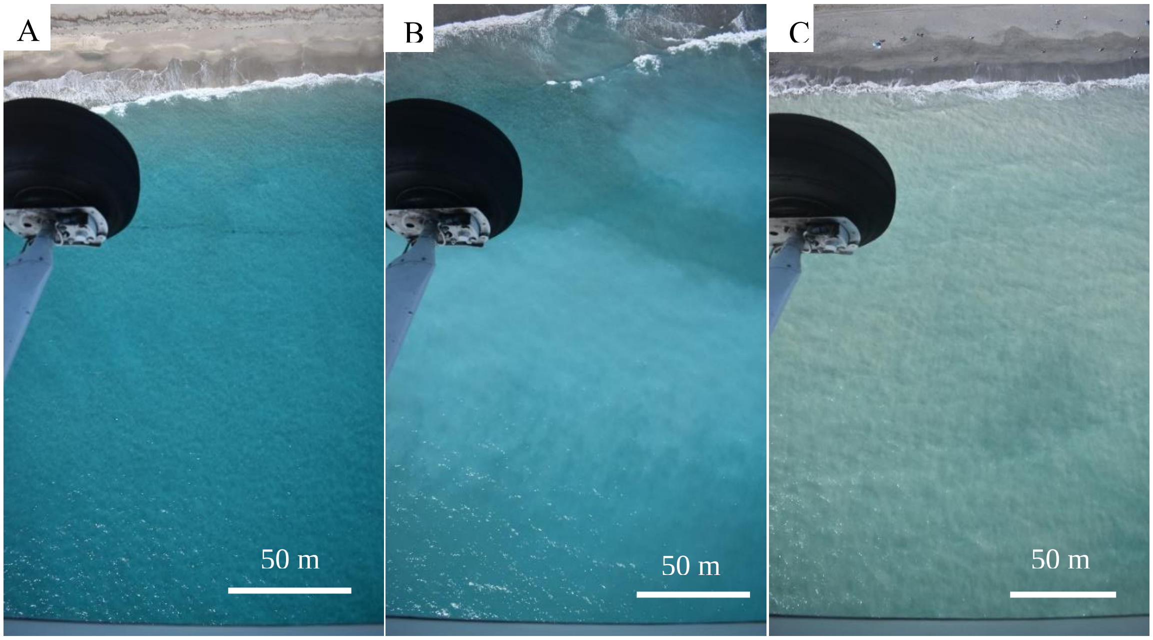

Figure 6.5 Photos from aerial surveys. A. South of study area, no turbidity. B. Offshore of the Juno Beach renourishment, turbidity: 3. C. Offshore of inlet adjacent renourishment, turbidity: 5

Results

In 2020 the blacktips arrived in mid-January and peaked in February with 600 individuals counted (Figure 6.6). The sharks decreased in population in March and by April only 25 individuals were observed. In 2021 the number of sharks counted peaked at 1371 in March and again by April most individuals had migrated north with 73 in April and 173 in May before all were gone in June 2021 (Figure 6.6).

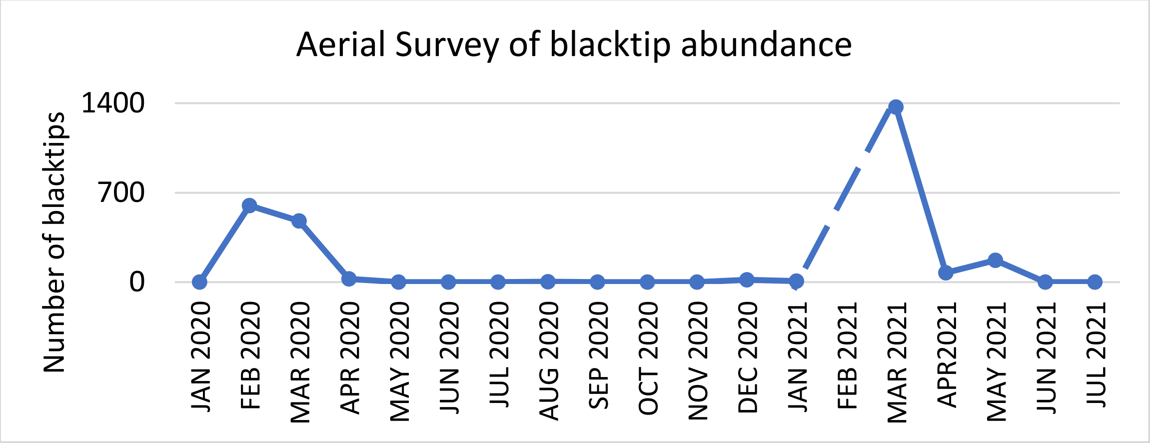

Figure 6.6 Aerial survey data from January 2020-July of 2021 displaying count of individuals between Palm Beach Inlet and Jupiter Inlet.

Blacktip shark abundance in 2020 was most common at the 50 m underwater cam location followed by the 100 m location (Figure 6.7). At the 50 m location in February, there were 126 sharks and seven at the 100 m. In March, two sharks were observed at the 50 m location and five at the 100 m. No sharks were seen at the 150 or 200 m cameras at any point of the 2020 migration period. Sharks were only observed in February and March of 2020 and had migrated north by April.

Fish species richness in 2020 was richest in February at the 100 m underwater cam location followed by the 50 and 200 m locations in February with 11, 5, and 4 different species, respectively (Figure 6.8). In March, the most species of fish were at the 200 m location with three species, followed by the 100 and 150 m locations each with two species. In April, the number of species of fish observed at the cameras shifted again with the most located at the 100 m location with four and the 50 and 200 m locations had two species each.

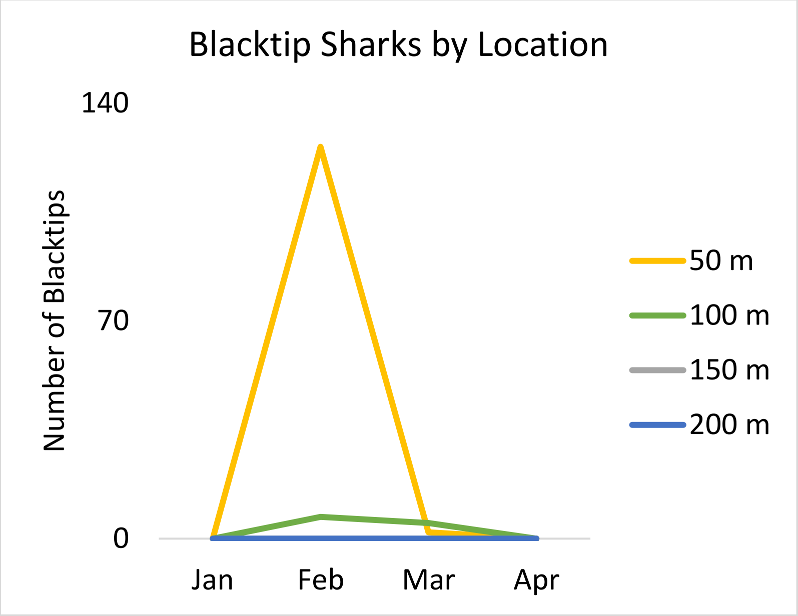

Figure 6.7 Cross-shore blacktip shark counts from underwater camera footage in 2020 between January and April.

The largest turbidity events were recorded during nourishment events and coincided with the blacktip shark migration to the region. From January 2020 to March 2020, seven aerial surveys were completed, however, images captured of sharks were limited to the southern portion of the study area south of the Park boundary. The images north of the Park captured plumes of at least 100 m in cross-shore width (Figure 6.9). It was during this same period that sediment was placed in the northern end of the study area from R13-R19. The project construction concluded in January 2020. The cross-shore extent of the turbidity plumes was averaged 150 m, with an average length of 7.2 km, and covering an area of 1.2 km^2. The largest plume captured in the aerial surveys was immediately after nourishment in January with a 13.5 km-long plume that covered 2.7 km^2 of the nearshore region (Table 6.1).

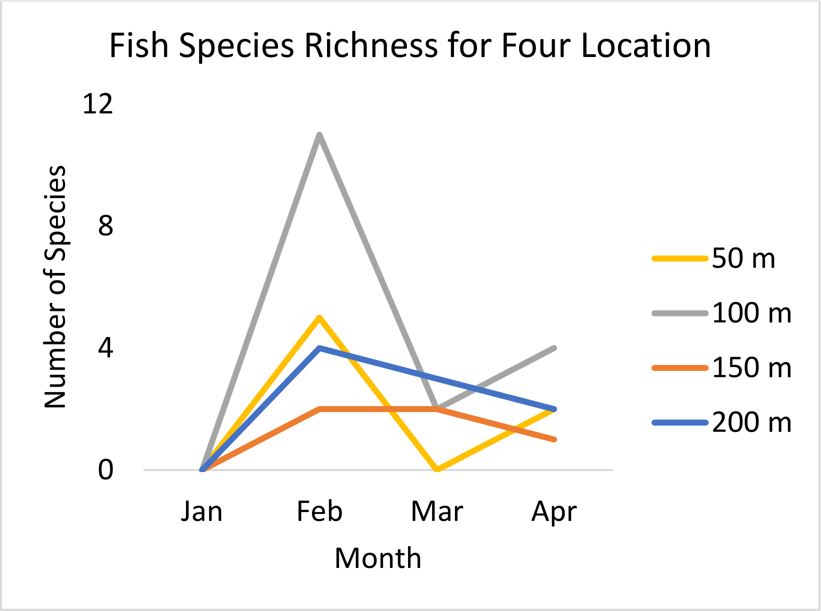

Figure 6.8 Cross shore species richness counts from underwater camera footage in 2020 between January and April.

Table 6.1 Turbidity plume records. *denotes river turbidity plumes

Survey Date	Turbidity Rating	Cross shore (m)	Length (km)	Area km^2
1/26/2020	5	200	13.50	2.70
2/4/2020	4	200	7.61	1.52
2/19/2020	4	100	5.33	0.53
2/28/2020	4	200	11.01	2.20
3/13/2020	4	100	3.15	0.32
3/24/2020	4	150	8.08	1.21
3/30/2020	2	100	1.69	0.17
6/15/2020	3*	250	0.60	0.15
6/15/2020	2	75	2.10	0.16
7/15/2020	0	-	-	-
8/29/2020	0	-	-	-
9/19/2020	3	150	9.08	1.36
10/14/2020	3*	250	3.15	0.79
12/5/2020	3	150	7.61	1.14
12/22/2020	2*	250	1.69	0.42
12/22/2020	5	250	4.41	1.10
1/10/2021	4	200	14.91	2.98
1/17/2021	5	200	12.01	2.40
1/24/2021	5	250	13.60	3.40
3/2/2021	4	200	7.35	1.47
3/30/2021	4	75	7.61	0.57
4/18/2021	4	150	12.01	1.80
5/13/2021	0	-	-	-
7/4/2021	2	50	3.81	0.19
8/23/2021	2	100	8.16	0.82
9/16/2021	0	-	-	-
10/16/2021	0	-	-	-
11/14/2021	0	-	-	-
12/2/2021	3	100	8.40	0.84
12/11/2021	4	200	11.95	2.39

Over the summer of 2020, two aerial surveys captured milky-colored turbid waters with an average length of 5.6 km over 1.4 km^2, and two surveys captured river-caused turbidity. The September 2020 turbidity was captured just after Hurricane Sally impacted the area (Briggs *et al.*, 2021). The cause of the June turbidity plume was not identified, however, it is known that it is not related to river discharge based on distinct color variations in the water (Figure 6.9).

The winter construction window of 2020-21 consisted of two nourishment events. One event placed sediment between R26-R38 and concluded in February 2021. The second event was within the boundaries of the previous event (between R14-R16) along the beaches just south of the inlet and concluded in April 2021. Eight aerial flight surveys were completed between December 2020 and May 2021. The images captured in all of the flights had turbid waters (Figure 6.9). The turbidity during these flights ranged from 75 and >250 m in cross-shore width. The plumes were on average 9.9 km long with an average area of 1.9 km^2. The two flights in December where turbidity plumes were present during the 2020-2021 construction window had an average length of 10.18 km and an area of 1.62 km^2. The longest turbidity plume captured was on 1/10/21 with a measured length of 14.9 km. However, the largest area of a plume was captured on 1/24/21, measuring 3.4 km^2. Along with the nourishment-related turbidity, on 12/22/2020 turbidity from river discharge extended into the study area of 1.69 km and encompassed an area of approximately 0.42 km^2.

Over the duration of the 2021 summer, two turbidity plumes averaged 5.99 km in length and 0.50 km^2 in area. The two plumes in the summer occurred in July and August and were not accompanied by any high-energy wave events. During the 2021 summer, there were no recorded river-related turbidity plumes. Turbidity plumes in December, marking the beginning of the 2020-2021 construction window, had an average length of

10.18 km and an area of 1.62 km^2. While the river discharge did not extend into the study area more than three times in the aerial surveys, it is still present in ebb-currents. It was observed within the inlet but did not intrude into the anthropogenic turbidity plumes most likely due to local currents (Figure 6.10).

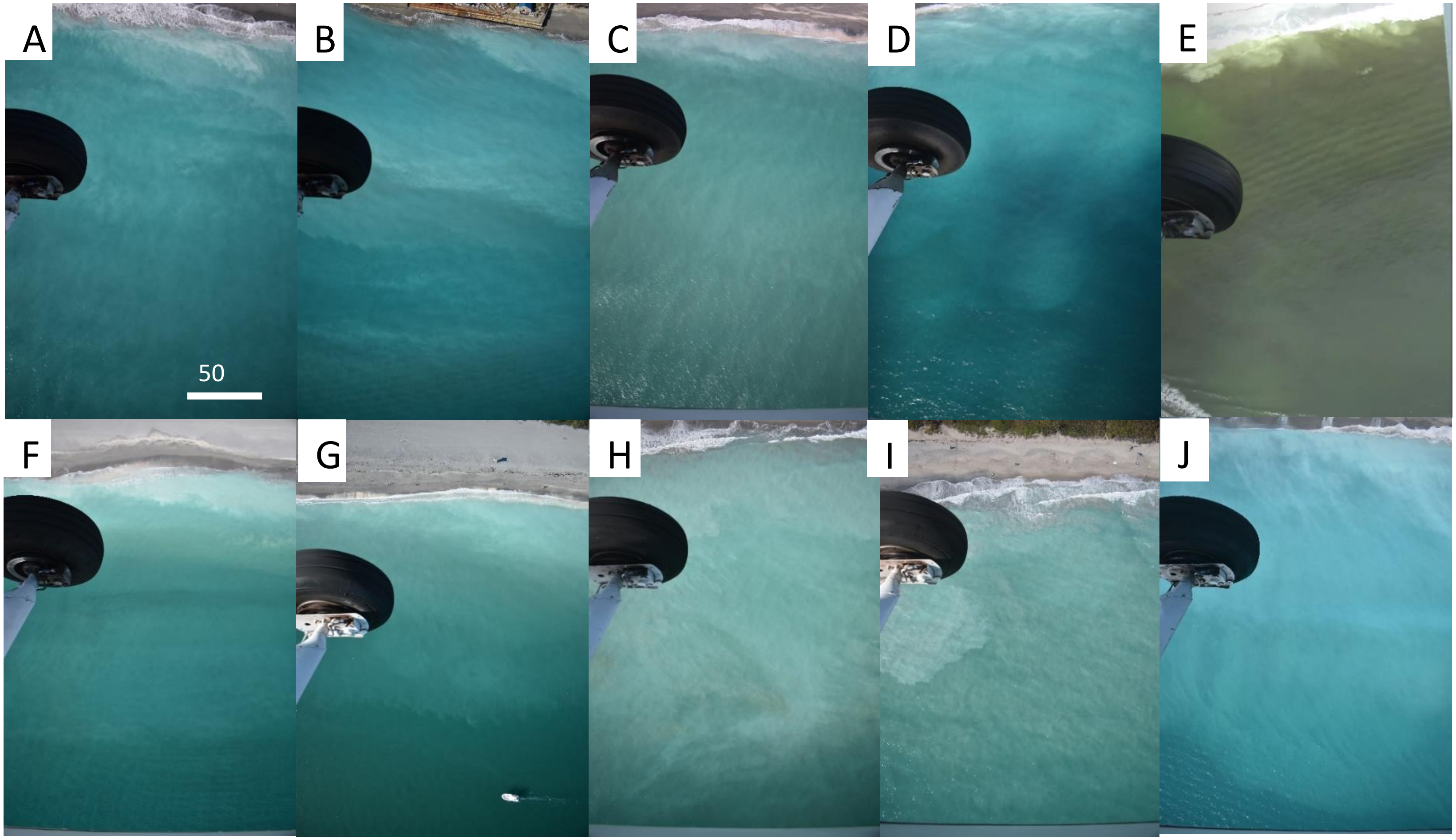

Figure 6.9: Aerial images south of the Jupiter Inlet displaying various levels of turbidity from different surveys: A. 1/26/20 B. 2/4/20 C. 3/11/20 D. 3/13/20 E. 6/15/20 F. 9/19/20 G. 12/5/20 H. 1/10/21 I. 1/24/21 J. 4/18/21 K. 6/15/20. Scale is equal for all photos

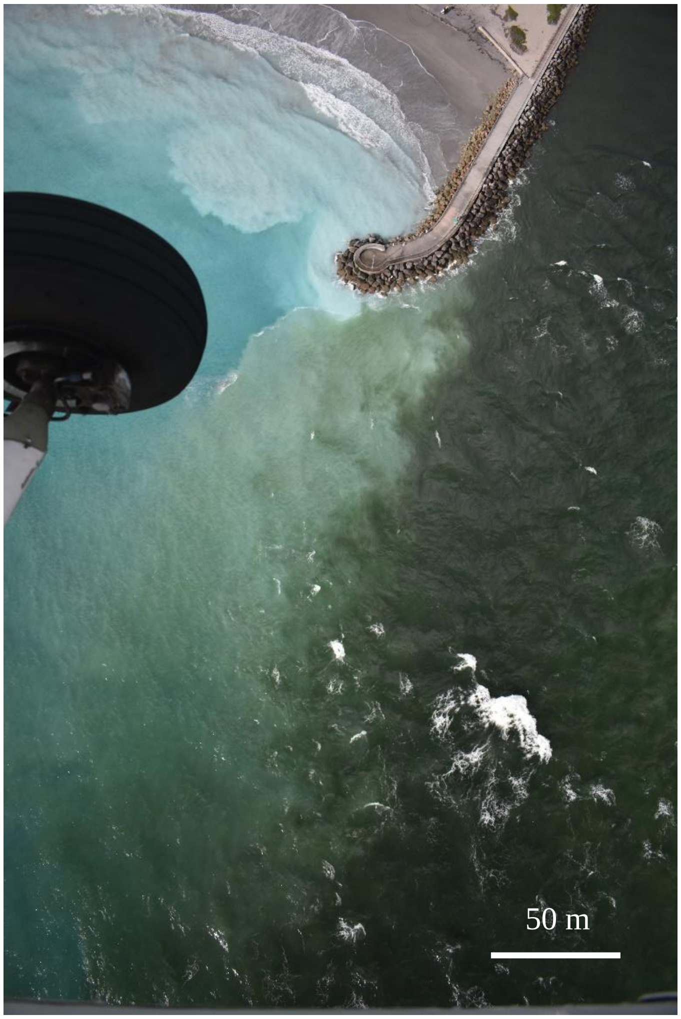

Figure 6.10: Aerial image of the south jetty of Jupiter Inlet displaying the river water slightly mixing with nourishment caused turbidity.

Discussion

Determining blacktip shark distribution by aerial survey within much of the study area was obscured by turbid waters. Whereas large aggregations of the sharks were observed congregating just offshore in the southern portion of the study area (Figure 1) from the aerial surveys in the late winter and early spring. Peak numbers of blacktip sharks were recorded in February in 2020 and in March 2021, with both migrations ending by late May. This large migration event is most prominently driven by temperature changes in the water (Kajiura & Tellman, 2016). From the underwater cameras in 2020, blacktips were recorded close to the beach (i.e., 50 m distance) and never exceed 100 m from shore. Furthermore, species richness varied cross-shore, but the blacktips were never more than 50 m (cross-shore) from the area of the highest species richness. Due to the rather consistent nearshore environment in PBC, the sharks likely prefer the various ridges and bars to both hunt and use as a refuge from predators. Further research is necessary to better understand the morphology where the sharks were observed along with research where turbidity plumes are occurring to determine if the sharks are leaving the area due to reduced visibility or if they are electing to stay there either because of prey, morphology, or temperature influences.

The nourishment project construction areas created turbid waters that were observed at various spatial extents. The average extent of sediment plumes has been recorded as generally < 500 m in length, confined to the swash zone, and the persistence should be from minutes to days (Greene, 2002; Roman-Sierra *et al.*, 2011; Van Dolah *et al.*, 1992; Van Dolah *et al.*, 1994 Burlas *et al.*, 2001). The nourishment-related turbidity plumes in this study recorded by aerial survey exceeded all three spatiotemporal extents. The average extent of the plumes exceeded 7 km consistently and the cross-shore extent was not limited to the swash zone as its average extent was beyond 150 m. The impacts of the transport of this fine-grained sediment needs further research due to the large discrepancy between the expected turbidity extents and the recorded extent. While the anthropogenic turbidity was consistent and intense, the less frequent occurrence (3 events) of natural turbidity plumes were short in duration as they were never seen in the study area in consecutive surveys and in relative area were smaller with an average area of 0.45 km2.

Implications of anthropogenic turbidity significantly outpacing natural turbidity in frequency, size, and intensity include concern for the blacktips that may not be adapted to these unnatural conditions along with other biota that are found in the same nearshore waters. Furthermore, concern is increased for potential shark-human interactions as the sharks are present during the peak tourism period in PBC. The extent and duration of the turbidity strongly suggest a need for a reevaluation of best management practices within the area including placement methods, silt screening techniques and technology, and sediment composition and grain size both on the beach and from the borrow source. Further suggestions for best management practices include a deeper examination by regulatory agencies on the impact of nourishment on important migratory nearshore species and an examination of potential impacts on local reef tracts as a result of the widespread turbidity.

Conclusion

Turbidity in coastal waters is an environmental problem that has numerous potential negative impacts. Not only is turbidity an environmental issue, but it also prevented aerial surveys of the blacktip shark aggregated within the study area. The blacktip shark migration is important ecologically to the nearshore along the US East Coast from North Carolina to South Florida. Understanding their aggregational habit is important not only to better understand the species but also to understand how changing physical conditions (e.g., bathymetric and sediment changes, turbidity, warming waters) impact these aggregations and migration extent. Another concern as a result of turbidity is the visibility reduction that influences many species including the blacktip shark's capacity to visually identify prey, potentially causing increased human-shark interactions. Overall, the impact of turbidity should be considered among other effects on the species' aggregation and migration patterns.

Additional research on causes, residency time, and extent of turbidity plumes is needed to evaluate best management practices that consider impacts on the nearshore habitat for not only the blacktips, but all other species impacted by extended turbidity events. Furthermore, for future studies on shark distribution in the vicinity of nourishment projects or where river plume turbidity is common, other methods for surveying the location and movement of sharks should be considered (e.g., acoustic devices, GPS tagging) in conjunction with the traditional aerial surveys.

CHAPTER 7: SUMMARY AND CONCLUSION

The main objective of this dissertation was to contribute to and improve the understanding of coastal system morphodynamics and sediment changes due to natural and anthropogenic processes and potential ecosystem impacts. This dissertation was organized into 5 distinct project to achieve each objective. Project 1 was a comprehensive literature review on the US continental shelf sediment distribution, dynamics, and bathymetric variability to present the current state of understanding and identify gaps in knowledge. Given the emerging acceptance that sediment is a valuable resource and is necessary for improving coastal resiliency, a comprehensive review was conspicuously lacking from the scientific community. This effort identified that continental shelf sediment characteristics and distribution need additional investigation to better establish databases mapping the location and quantifying geotechnical properties. Regionally extensive evidence of the impact of storms on sediment ridges located on the shelf was lacking in the literature, despite some studies documenting migration due to the potential of extreme wave events to transport a significant amount of sediment. Finally, although several studies have focused on changes to the actual borrow pit (e.g., cut shape, infilling rate), the broader impacts of dredging on the continental shelf from sediment extraction are needed to ensure best management practices for this limited resource that is necessary for long-term coastal conservation.

In project 2, the sedimentology and morphology of the beaches in Northern Palm Beach County were examined to establish a baseline for sediment granulometry, composition, and overall beach characteristics (such as slope). Sediment at the mid-beach ranged from moderately well sorted to poorly sorted, medium to coarse. The general trend was coarser sediment near the inlet and finer downdrift. Sedimentological analysis of both the bulk and non-carbonate sediment had not been previously completed within Palm Beach County. The McFall (2019) beach slope predictions were accurate for the protected coast beach conditions for the study area. The results of this study suggest that locally calibrated empirical tests to determine beach slope predictions based on grain size are needed to account for variable geographic conditions (e.g., a combination of wave dissipation from the general bar and trough morphology and reduced fetch due to the Bahamian archipelago).

Project 3 examined inlet adjacent morphologic and sedimentologic changes to the beach-nearshore system where both anthropogenic and natural influences are known to alter the beach-nearshore system. Quantifying the cause and magnitude of external forcing on the beach system is necessary to ensure the beach environment continues to function as a storm buffer and reduce flood impacts, provide habitat, and support the community through recreation, tourism, and the economy. Although storms are natural events, the active 2020 hurricane season induced widespread erosion in the study area resulting from consecutive storms, especially on non-nourished beaches. Nourished beaches were less prone to large quantities of sediment loss and recovered more rapidly. Anthropogenic influences on beach morphology and sedimentology included nourishment and impacts of hard structures. Large volumes of sediment on the beach altered the nearshore morphology and sedimentology through the profile equilibration process resulting in a more monotonic bathymetry with coarser sediment. The morphodynamic understanding of coastal systems is grounded in the principles of feedback where sediment transport (and the sediment characteristics) drives morphology change that can alter hydrodynamic conditions for subsequent changes in sediment transport rates and morphology change. Quantifying the natural and anthropogenic influences along regionally distinct beach types (e.g., inlet-adjacent, nourished, non-nourished) is fundamental to coastal management and development of adaptation pathways for future coastal restoration and community planning.

Ecological impacts of natural and anthropogenic influences were examined in projects 4 and 5. Project 4 examined the nesting behavior of loggerhead sea turtles and the impacts of the physical beach environment on hatching and emergence success. Loggerhead nesting success was higher on wider, nourished beaches. Hatching and emergence success was most significantly impacted by morphologic changes from storm-induced erosion and accretion. The objective of project 5 was to examine blacktip shark aggregations relative to the physical nearshore environment and the potential impacts of dredge and placement for nourishment projects. Instead, reduced water quality from extensive turbidity plumes extending well beyond the typically expected spatiotemporal extent were documented during the two-year study period. The poor water clarity prevented surveying the blacktip shark aggregates and changes in behavior directly within the project area. However, blacktip sharks were quantified just south of the study area where peak populations were found only 50 m from the shoreline during February 2020 and March 2021. Their preference of shallow water in close proximity to the shoreline suggests that the persistent turbidity plumes could be a nuisance for their capture of prey. Further study is recommended within turbidity-producing project areas using alternative methods such as tagging to investigate the impacts of changing water clarity on the blacktip shark locations, prey acquisition, and migration patterns.

In summary, over the two-year study, nourished beaches were more resilient, wider (increased storm protection), and provided more habitat for nesting sea turtles. No adverse impacts were found on loggerhead nesting, hatching, or emergence success from restoration activities. However, the construction window for these projects overlaps with blacktip shark migration and the process of construction led to numerous, persistent turbidity events. These results demonstrate the benefits of beach nourishment but suggest further research is needed into how project construction may impact other nearshore fauna, such as the blacktip sharks. Coastal managers may consider revisiting best management practices for coastal resiliency of beaches, sediment resource management, and habitat conservation efforts.

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