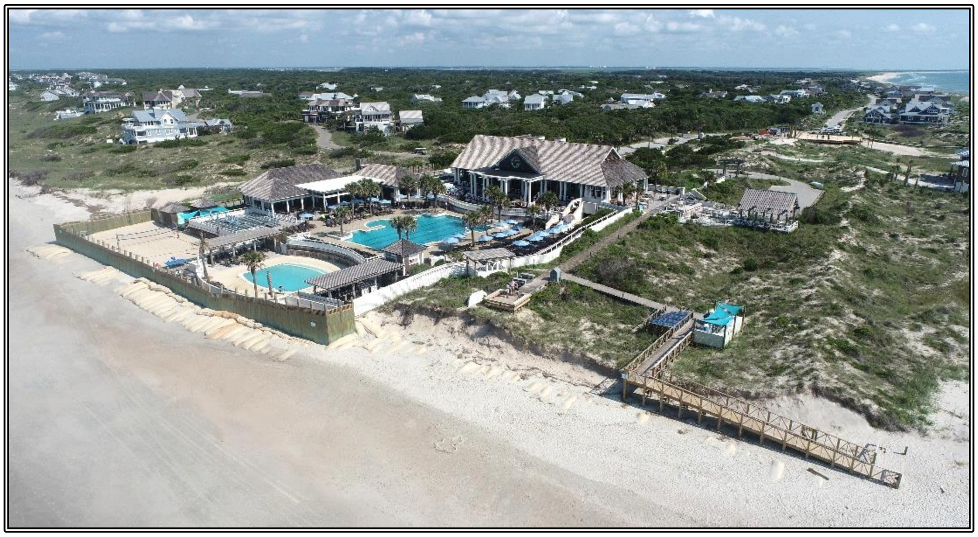
SHOALS CLUB EROSION STUDY

BALD HEAD ISLAND, NORTH CAROLINA

SEPTEMBER 2023



PREPARED FOR

SHOALS CLUB

PREPARED BY

COASTAL PROTECTION ENGINEERING OF NORTH CAROLINA, INC.
ENGINEERING LICENSE CERTIFICATE #: C-2331

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EXECUTIVE SUMMARY

This report documented the study of the causes of the long-term erosion and accretion that has occurred along the Shoals Club shorefront during the last two decades. Previous studies related to the morphological changes that have occurred in the area were reviewed and incorporated into this study where appropriate. Recent topographic and bathymetric survey data, LIDAR data, and historical aerials were used to evaluate shoreline and volume changes and understand sediment transport pathways. Likewise, topographic and bathymetric data as well as wave data were compiled to perform a wave modeling analysis. These analyses were synthesized to develop an understanding of the recent erosion trends. Based on the results of these analyses, six alternatives aimed at mitigating the recent erosional impacts were presented.

Review of the historic aerial imagery proximate to the Club revealed the link between the orientation of the Cape Fear point and width of the dry beach in front of the Club. When the point is oriented to the south, it acts as a barrier to easterly transported sand along South Beach. Transported sand is impounded on the point, resulting in updrift accretion and an increase in beach width. It is believed that this mechanism is the primary driver of accretion along the Club's shorefront. When the point is oriented to the east, southerly transported sand on East Beach is impounded on the point, which, in turn, results in accretion and an increase in beach width along southern East Beach. Analysis of the beach profile volume change and MHW shoreline position changes along South and East Beaches confirm these observations.

The wave modeling analysis revealed an alongshore variation in wave heights along East and South Beach. That is, wave heights decrease with increasing proximity to the point. The modeling results indicated that a relatively small fraction of the offshore wave energy actually reaches the beach in front of the Club. This variation in wave height induces an alongshore hydraulic gradient on both South and East Beaches, resulting in point-directed alongshore currents. These alongshore currents intersect at the tip of the Cape Fear point. When one current overpowers the other, the tip of the point reorients accordingly. Along South Beach, this alongshore (cross-shoal) current meanders through Frying Pan Shoals based on shoal locations and strength of currents. When the point is oriented to the south, it pushes the cross-shoal current further offshore and away from the Club's shorefront. When the point is oriented to the east, the current often meanders immediately offshore of the Club's beach and causes increased erosion rates along eastern South Beach. The cross-shoal current is reinforced by the local wave refraction patterns near the point, which directs waves toward Frying Pan Shoals. This meandering cross-shoal current is believed to be the primary driver of erosion along the Club's shorefront.

Powerful winter cold fronts and summer hurricanes are capable of reorienting the point in a short period of time. During the summer of 1999, Bald Head Island was impacted by three powerful hurricanes, including Hurricane Floyd in September, which made landfall near the Island. These hurricanes reoriented the point to a southwesterly orientation and caused a westward transport of nearshore sand across East Beach and Frying Pan Shoals. The westward transported sand potentially clogged the cross-shoal channels within Frying Pan Shoals, setting up ideal conditions for the southward advance of the point. The following years exhibited relatively calm wave conditions, maintaining the point in a southerly orientation. From 1999 to the summer of 2006, the point and the MHW shoreline in front of the Club steadily advanced to the south by hundreds of feet. In September 2006, Tropical Storm Ernesto made landfall on Oak Island to the west of Bald Head Island and likely caused powerful cross-shoal currents to reorient the point in a more easterly direction, allowing cross-shoal channels to meander closer to the point. From summer 2007 to May 2022, the point and the MHW shoreline in front of the Club steadily retreated hundreds of feet, which forced the Club to install a temporary sandbag revetment in June 2022.

Six alternatives aimed at mitigating the recent erosional impacts and slowing erosion rates along eastern South Beach were developed for the Club's consideration. Each alternative was developed to mitigate the erosion concerns with a different approach in order to improve overall cost and/or ability to acquire state and federal permits. **Table i** summarizes the implementation schedule as well as the approximate costs of each alternative. These estimates are for preliminary budget purposes only and are presented in 2023-dollar values. These estimates may be refined during value engineering and final design. CPE has no control over the timing, availability, cost of labor, equipment or materials, market conditions, or methods that may affect future pricing. Accordingly, no warranty can be provided that the actual bids or negotiated prices will not vary from these estimates.

Table i: Summary of implementation schedule and approximate project cost.

Alternative	Strategy	Implementation Schedule (years)	Approximate Project Cost
1	Beach Renourishment	1-2	$1,450,000
2	Dredge Cross-Shoal Channel	3-4	$5,170,000
3	Point Sand Transfer	1-2	$1,300,000
4	Geotube Groin Field	3-5	$1,050,000
5	Terminal Groin	3-5	$7,410,000
6	Managed Retreat	1	$2,150,000

SHOALS CLUB EROSION STUDY

BALD HEAD ISLAND, NC

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1. INTRODUCTION

This report documents the study of the causes of the erosion that have impacted the oceanfront property of the Shoals Club (Club) during the last decade and offers recommendations aimed at mitigating these erosional impacts. Previous studies related to the morphological changes that have occurred in the area were reviewed and incorporated into this study where appropriate. Recent topographic and bathymetric survey data, LIDAR data, and historical aerials were used to evaluate shoreline and volume changes and understand sediment transport pathways. Likewise, topographic and bathymetric data as well as wave data were compiled to perform a wave modeling analysis. These analyses were synthesized to develop an understanding of the recent erosion trends. This report provides insight into the factors likely to be influencing shoreline change adjacent to the Club and provides options aimed at preventing future impacts to the Club.

1.1 Background

When the Shoals Club was originally constructed in 2004, there were approximately 550 ft and 700 ft of beach from the Club to the waterlines to the south and east, respectively. A detailed assessment of historic aerial photography indicates that since that time, the proximity of the waterline to the Club along both eastern and southern shorelines has varied substantially, but eastern South Beach has been consistently erosional since around early 2007. More specifically, and the impetus for the development of this study, the southern shoreline eroded to the point that elevated wave events threatened to impact the Shoals Club infrastructure, motivating the Club to install a sandbag revetment in June of 2022 (Olsen, 2022a). Despite substantial variability, the width from the Club to the eastern shoreline has remained sufficiently wide since construction of the Club to prevent impacts from occurring to the property from that shorefront.

In May 2023 the Club contracted with Coastal Protection Engineering of North Carolina, Inc. (CPE) to perform engineering analyses of the recent erosion proximate to the Club and develop conceptual alternatives aimed at mitigating the erosion that threatens the Club infrastructure. Accordingly, this report presents the results and conclusions of the various analyses and provides recommendations for future mitigation strategies.

1.2 Geographic Setting

The Club is located on the southeastern tip of Bald Head Island in Brunswick County, North Carolina. Bald Head Island (BHI) is about 30 miles south of Wilmington and is the southernmost barrier island of the Smith Island Complex, bordered by the Atlantic Ocean on the east and south, the Cape Fear River to the west, and Bald Head Creek to the north. Figure 1 presents an overview of the Bald Head Island geographic setting as well as notable features in the vicinity of the Club.

The Club is situated at a geologically unique location at the intersection of two, broad arcuate embayment features along the Atlantic Ocean coastline: Onslow Bay to the north and Long Bay to the south. These two bays converge at the Cape Fear foreland, resulting in two, near-perpendicular shorelines adjacent to the Club: East Beach to its east, and South Beach to its south. East and South Beach connect at the sandspit historically referred to as the Cape Fear "point". South Beach is approximately 3.3 miles long and extends from the Cape Fear River to the point. It is largely developed with single-family homes. East Beach extends around 5.6 miles to the north from the Cape Fear point to Fort Fisher State Recreation Area and is mostly undeveloped (Cleary, 2008). West Beach is about one mile long and extends along the western side of the island, fronting the Cape Fear River.

The Cape Fear River entrance is located between the Smith Islands (Bald Head, Middle, and Bluff Islands) to the east and Oak Island to the west as depicted in **Figure 1**. The US Army Corps of Engineers (USACE) maintains the federal navigation channel along the Cape Fear River that connects the Atlantic Ocean to the Port of Wilmington. The federal channel extends roughly 7 miles offshore in a south-southwest direction. The USACE began maintaining the channel in the late 1820s through reoccurring dredging and deepening/widening operations. Since the 1990s, beach compatible material dredged from the channel has been placed on South Beach and Oak Island. The majority of this material has been placed along the western half of South Beach (USACE, 2014).

The littoral drift that creates the sandspit has historically been directed from north to south along East Beach and from west to east along South Beach. Evidence of this drift can be observed in the historical aerials presented in **Appendix B** and has been additionally documented in numerous reports (Olsen monitoring reports, Olsen 1989, USACE 2014). Littoral material is transported from the beach and nearshore region into the offshore shoal feature known as Frying Pan Shoals by winds, waves, and nearshore currents. The shoals comprise a vast volume of sand, approximately 1.4 billion cubic yards (cy) and extend roughly 20 miles to the southeast from the Cape (USACE, 1977). **Figure 2** presents a bathymetric map of the broad shoal feature and its proximity to the Shoals Club. The prominence of the Frying Pan Shoals complex has a significant effect on the local wave climate, which is discussed in subsequent sections of this report.

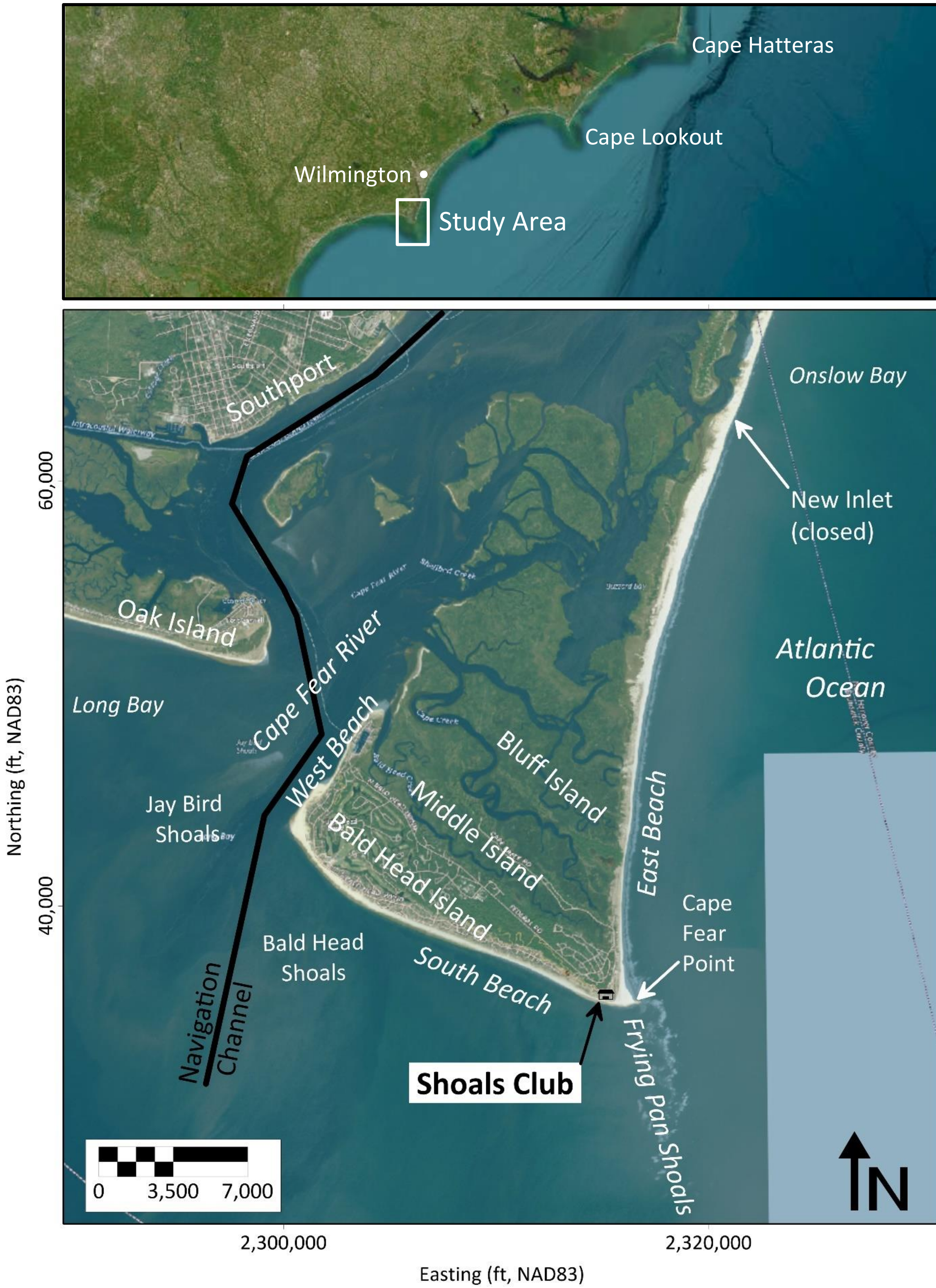

Figure 1: Overview of the location of the Shoals Club on Bald Head Island.

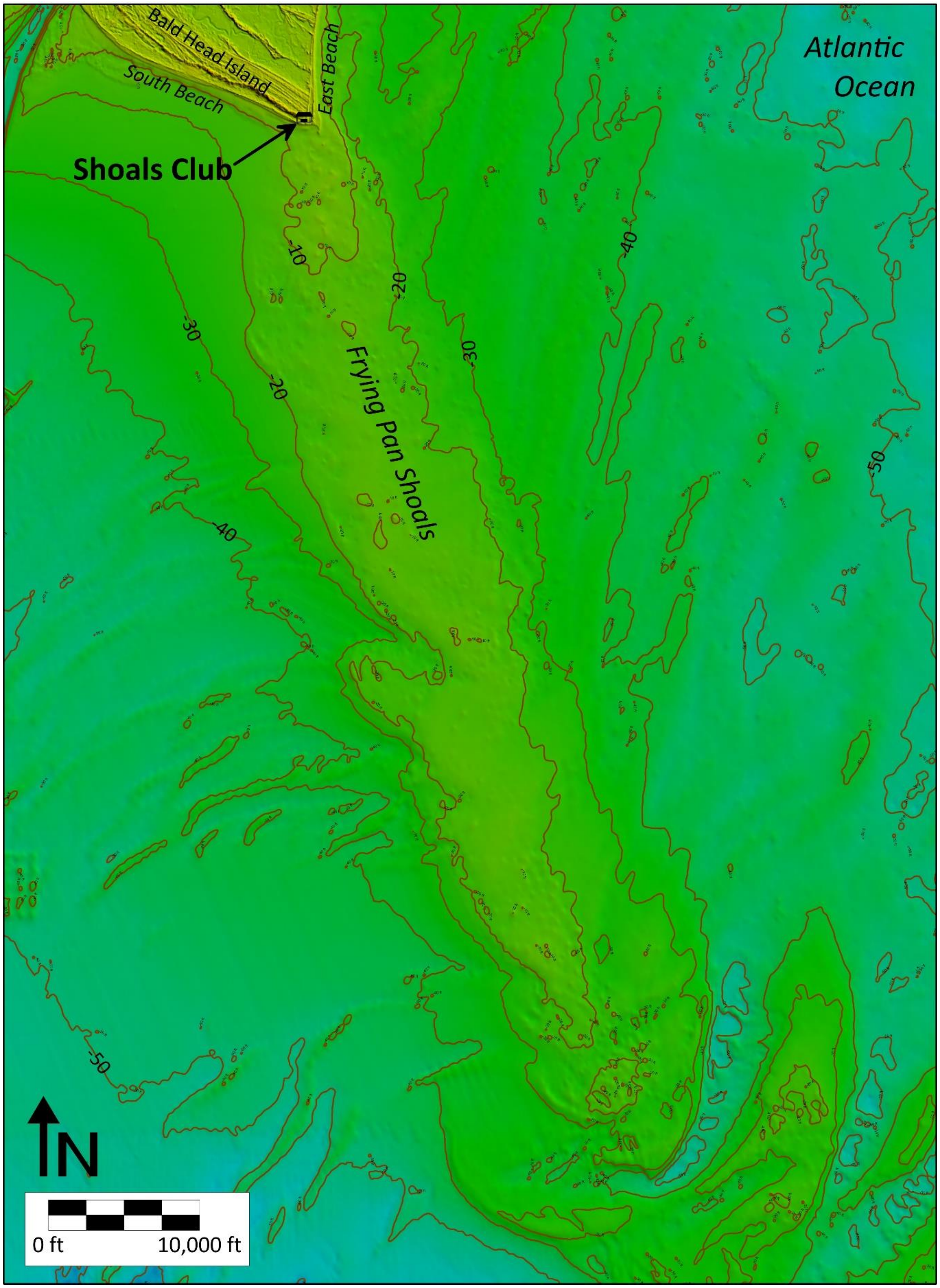

Figure 2: Bathymetric map of Frying Pan Shoals illustrating the broad expanse of the shoal complex. Depths in feet (NAVD88). Data downloaded from https://www.ncei.noaa.gov/maps/bathymetry/.

1.3 Oceanographic Setting

The study area is subject to the typical seasonality of the Atlantic Ocean along the east coast of the United States, i.e., elevated wave conditions during the winter months due to strong, prolonged northeasterly winds and typically smaller wave heights during the summer months, with occasional disruptions to the calmer conditions due to the passing of tropical systems from June to November. The astronomical tides in the area are semi-diurnal and can vary as much as 5 ft vertically (USACE, 2014).

The Cape Fear headland, upon which the Shoals Club is located, is the southernmost cape (headland) feature in North Carolina, with Cape Lookout and Cape Hatteras located to the northeast. The orientation of these two northern capes provides a degree of sheltering from waves originating from the north and northeast. The continental shelf is located approximately 50 to 100 miles offshore of BHI and is oriented from southwest to northeast, which generally orients offshore waves to arrive from the east-southeast direction (see **Figure 1**).

Since the mid- to late-1900s, the sea level at Bald Head Island has risen on the order of 3 mm/yr (0.118 in/yr), on average, based on sea level rise rates[1] interpolated between Wilmington Harbor and Myrtle Beach, SC. Projecting this rate of rise over the timeframe since construction of the Shoals Club around 2004 suggests local relative sea level rise is in the order of approximately 2 inches. It is not expected that this increase in sea level has had a substantial contribution to the recent erosion experienced at the Shoals Club when compared to the more impactful forces of elevated waves or the alongshore currents near the Club's shorefront; therefore, the implications of this phenomena were not expressly investigated in this study.

1.4 Previous Dredging and Coastal Protection Activities

The earliest dredging activities in the BHI area involved dredging the Cape Fear River navigation channel in the early 1820s to maintain safe navigation. Since then, the channel has been regularly maintained (dredged) as well as realigned, widened, and deepened to accommodate increasing vessel sizes and improved channel alignment (USACE, 2014). **Table 1** lists the various channel improvements since 1925.

[1] Trend data taken from https://tidesandcurrents.noaa.gov.

Table 1: Cape Fear River Channel Improvements (1925 to present).
Adapted from USACE (2014).

Year Constructed	Depth (ft below MLW)	Width (ft)
1925-26	30	400
1949	32	400
1956	35	400
1968	40	500
2000	44	500

To mitigate chronic erosion issues experienced along the Village of Bald Head Island's (Village) West and South Beach, beach compatible material dredged from the navigation channel and the river's ebb shoals has been systematically placed along varying extents of South Beach. Since 1991, approximately 13.2 million cy have been placed along portions of South Beach and western BHI (West Beach) (Olsen, 2022a). **Figure 3** illustrates the history of the beach renourishment activities along South Beach. As indicated in the figure, the western half of South Beach has been the primary recipient of placed sands. The most recent beach nourishment project in 2021 involved the closest placement of fill material along the shoreline in proximity to the Shoals Club.

To complement the erosion mitigation efforts along western South Beach, a groin field of 16 sand-filled, geotextile tubes were initially installed in 1996. The groins have been repaired and replaced on a few occasions and are generally accepted to perform their intended function of decreasing local erosion rates and shoaling into the navigation channel (Olsen, 2022a). The eastern and western extents of the groin field are located approximately 2.2 and 3.2 miles from the Shoals Club, respectively. Given the net westerly-directed alongshore sediment transport in the area and distance from the Club, it is not expected that this groin field is related to the recent erosion experienced along the beach in front of the Club.

Following years of beach renourishment, beneficial disposal of navigation dredging material, and the installation of sand-filled geotubes, continued chronic erosion along the western end of South Beach prompted the Village to construct a 1,300 ft long terminal groin structure in the spring of 2015 at the western end of South Beach, adjacent to the navigation channel. The structure was constructed approximately 3.2 miles to the west of the Club. The terminal groin's design purpose was to capture westerly transported sand before it either was deposited in the channel or transported upriver along West Beach, and the captured sand would provide additional protection to the upland infrastructure from the ocean. Coincident with the terminal groin construction, the westernmost three geotube groins were removed from the beach (Olsen, 2022a). Similar to the remaining geotube groin field, the terminal groin is not suspected to have contributed to the erosion experienced along the beach in front of the Club due to the net westerly-directed sand transport in the vicinity of the groin as well as its overall distance from the Club.

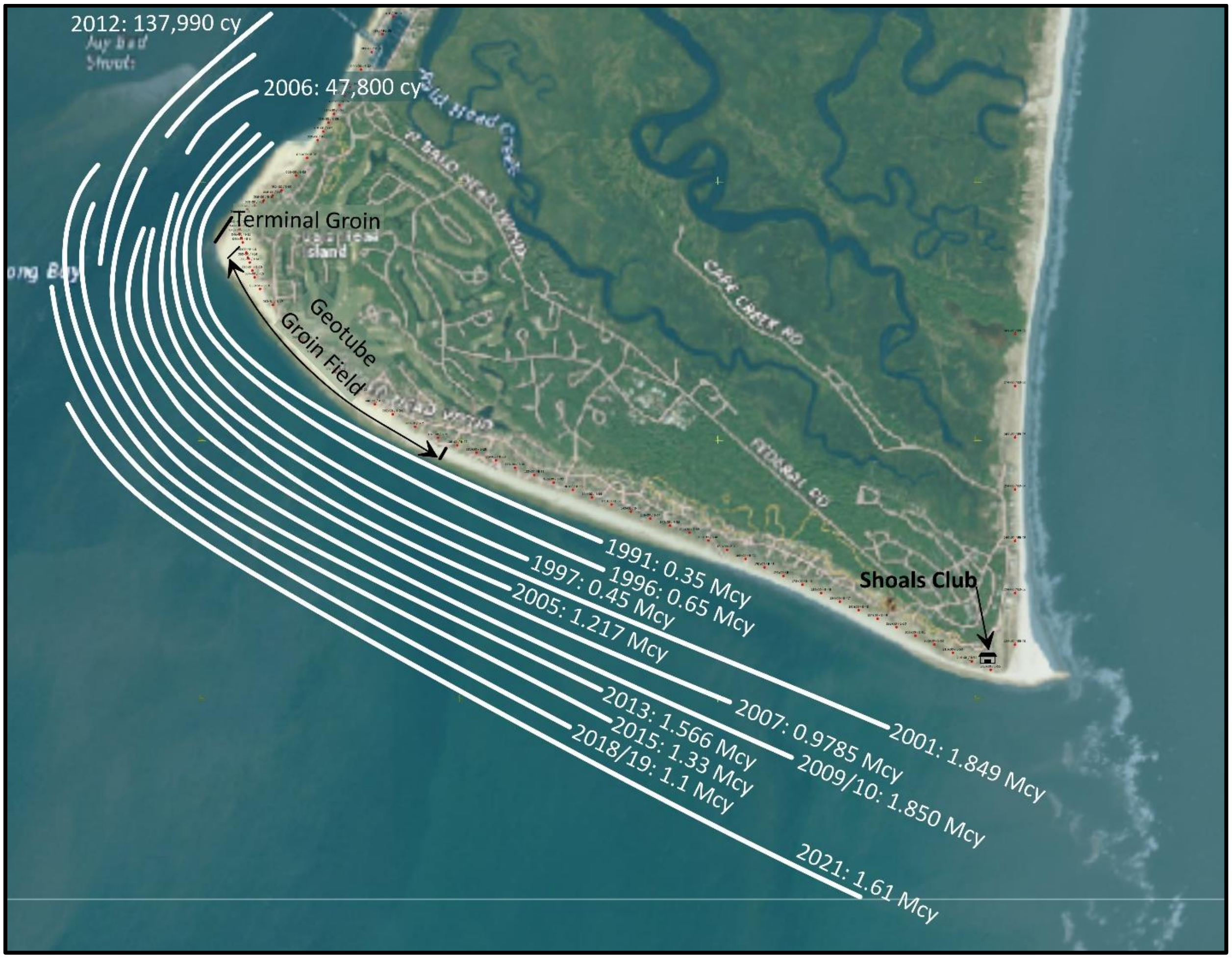

Figure 3: Year, volume, and extents of beach renourishment projects on Bald Head Island since 1991. Adapted from Table 1.2 in Olsen, 2022a.

Despite the addition of millions of cubic yards of sand to South Beach over the years, recent erosion experienced along the southeastern end of the island prompted the Club to install a sandbag revetment in June 2022 to prevent impacts to the Club infrastructure (see **Figure 4**).

No documentation for any previous coastal construction along East Beach north of the Club was found during the literature review portion of this investigation. In 2017 the Village initiated the permitting process for use of a portion of Frying Pan Shoals, south of the Club, as a future sand borrow area for beach nourishment projects. The borrow area is located around 1 mile offshore of the Club (Olsen, 2016) and is depicted in **Figure 5**. The permit application has been stalled in the Request for Additional Information (RAI) stage without a clear indication that the permit will be authorized in the near future (Olsen, 2022a).

Figure 4: Sandbag revetment placed in front of the Club in June 2022. Photo from July 2023.

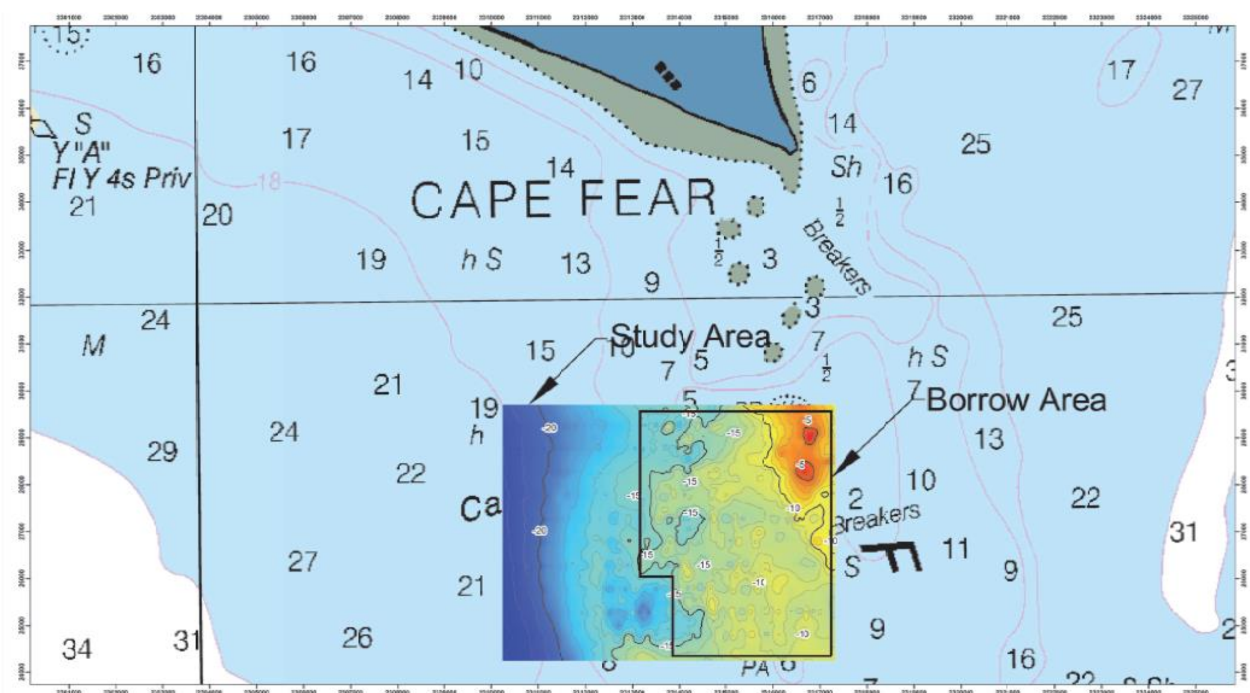

Figure 5: Borrow area proposed by the Village in 2017 for beach renourishment projects along South Beach (Image from Olsen, 2016).

2. LITERATURE REVIEW

Due to the unique geology of Cape Fear and the federal involvement in the maintenance of the Cape Fear River navigation channel, the shorelines of Bald Head Island's beaches and waterways have been studied since at least the mid-twentieth century. The following paragraphs summarize studies relevant to the Shoals Club shorefront to provide historical context and improve the understanding of the morphological mechanisms at work in the area. Based on the premise that the regional stability of the Shoals Club's southern and eastern shorefronts are primarily influenced by the configuration of the point and sub-aerial shoals, particular attention was given to previous studies that discussed the variability of the Cape's configuration over time.

2.1 El-Ashry and Wanless, 1968

This study relied on aerial photographs and published nautical charts to characterize shoreline changes at select locations through North Carolina, including Cape Fear. During the period from 1929 to 1962, the authors estimated that the southern tip of the cape advanced southward by as much as 1,500 ft, with intermittent periods of shoreline advance and retreat of over 1,000 ft on a near decadal scale. The cause of this substantial shoreline position change was not directly discussed. However, the report mentioned the profound effect that two particular storms had on the configuration of the cape during this time period: the Great Atlantic Storm of 1962 and Hurricane Helene in 1958. The former storm reversed around 17 years of cape accretion and stability, and the latter reoriented the cape tip from the southeast to the southwest. **Figure 6** presents the aerial imagery during the 17 years from 1945 to 1962 published in the study. The images demonstrate the variability in the configuration of Cape Fear, which the authors indicate was a result of prevailing gale-force winds and non-tidal currents. The influence of the non-tidal currents can be observed in the 1959 image as the current appeared to divide the point as well as in the 1962 image as a current alongshore eastern South Beach redistributed sand to the east of the cape tip beyond the East Beach shoreline.

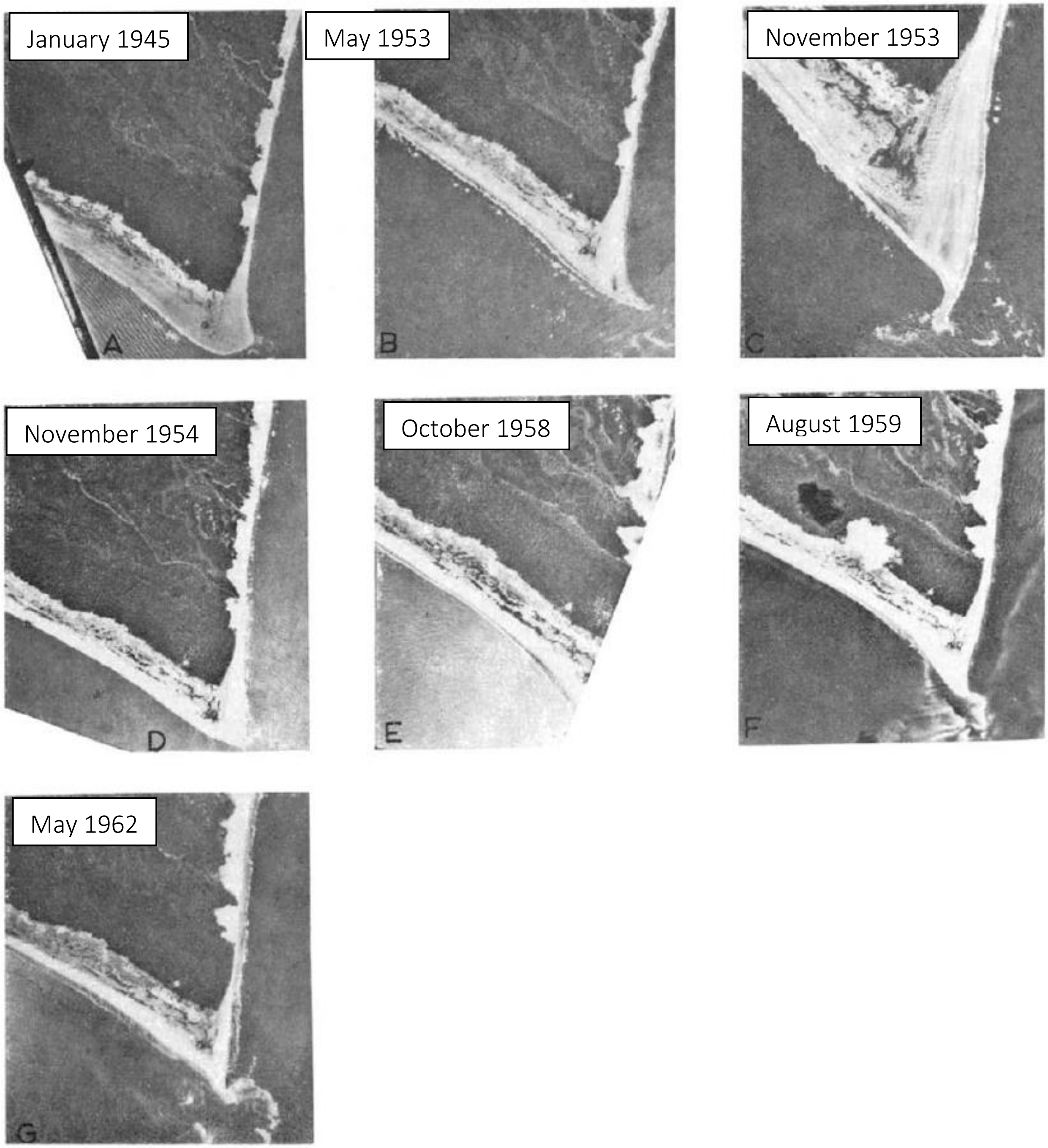

Figure 6: Aerial photography of Cape Fear from 1945 to 1962. Image from **El-Ashry and Wanless**, 1968.

2.2 Olsen Associates, Inc., 1989

This study analyzed the feasibility of beach renourishment on BHI as a potential means of erosion mitigation along the island's South and West Beaches. As part of the study, an in-depth review of historic shoreline positions and beach volume changes was conducted as well as a wave refraction and littoral transport study. The results of these analyses suggested that the federal maintenance of the Cape Fear River navigation channel likely contributed to the erosion issues experienced along the western half of South Beach. However, the report also indicated that approximately 2.5 million cy of sand accreted along the eastern third of South Beach since the Cape Fear River navigation channel improvements began from around 1870 to 1975. The study did not directly tie the increase in beach volume in this area to the channel improvements.

Previous investigations referenced in the study suggested that sand on East Beach was transported either to the south to Frying Pan Shoals or to the west along South Beach, then West Beach. However, the Olsen study reported that this transport pattern was not apparent through review of shoreline and beach volume changes along West, South, and East Beaches. Instead, the study found no clear relationship between erosion and accretion trends along the three shorelines. It is noted, however, that the study was generally investigating trends across the entirety of BHI and not specifically of those near the Cape Fear point. In contrast, the present study found a clear inverse relationship between erosion and accretion trends along the eastern portion of South Beach and southern portion of East Beach where the Club is located.

The wave refraction and littoral transport portion of the Olsen study indicated that a sediment transport "nodal" point exists on South Beach near Starrush Trail, which is approximately 2 miles west of the Shoals Club. West of the nodal point, the average annual wave energy directs sediment transport to the west from the vicinity of Starrush Trail to the west end of South Beach. This result can be confirmed qualitatively by inspection of the historic aerials in **Appendix B,** where sand is trapped on the eastern side of the geotube groins at the western end of South Beach. Between the nodal point near Starrush Trail and the east end of South Beach, the study concluded that sediment transport is to the east. This result indicates that the Shoals Club shorefront is limited to receiving sediment from an area only 2 miles long. **Figure 7** illustrates the calculated alongshore sediment transport patterns and relative rates from the Olsen study. Inspection of the variation in length of the arrows proximate to the Club suggests that this study calculated that more sand exits the Club shorefront than enters it, which ultimately leads to beach erosion and shoreline retreat. This finding explains why the beach proximate to the Shoals Club has eroded in the past, but it does not explain why the same shoreline has experienced significant accretion during other time periods.

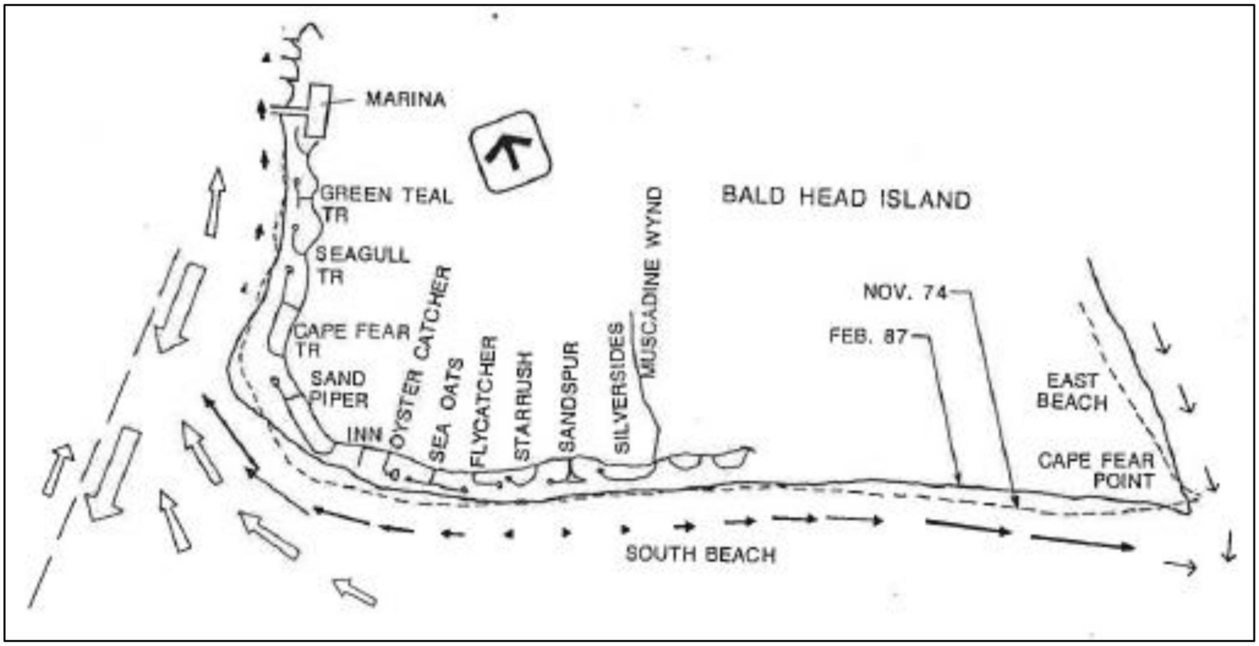

Figure 7: Average annual wave-induced longshore transport patterns (solid arrows) and tidal current flows (outlined arrows) along Bald Head Island. Copied from Olsen, 1989.

2.3 Cleary, 2008

This report provides a historical review of shoreline and inlet evolution across coastal North Carolina. Details are provided regarding the recurring opening and closing cycle of New Inlet, which had been located between roughly 5 and 8 miles north of the Cape Fear point during various time periods. The existence of an inlet is usually characterized by the formation of an ebb and flood shoal. The report indicated that prior to 1881, the New Inlet ebb shoal contained at least 50 million cy of material seaward of Fort Fisher. Following the inlet's closure that same year, the ebb shoal collapsed and migrated shoreward, supplying sediment to the beaches to the south. It is possible that some of the intermittent accretional periods during the early- to mid-1900s at the Cape Fear point could be related to episodic pulses of this ebb shoal sand reaching the point. Between 1895 and 1960, this cycle of inlet opening, migrating, and closing recurred three times. Review of the Google Earth Engine timelapse (https://earthengine.google.com/timelapse/) indicated that the latest closing of New Inlet occurred in 1999.

2.4 Olsen Associates, Inc. Monitoring Reports

Olsen Associates, Inc. has been regularly monitoring the BHI shoreline since 2003. The annual reports provide a summary of historical erosion control activities, contemporary beach profile volume and shoreline position changes, and in-depth discussion of ongoing or future work to be conducted for the Village's shoreline protection program. The reports also document the configuration of the Cape Fear point with aerial imagery as well as provide a brief description of recent shoreline position change trends at beach profile monitoring stations B-54 and B-55, located in front of the Club. The influence of the point on the adjacent South and East Beaches is briefly highlighted, and the point's evolution is described as a result of episodic storm events.

3. ANALYSES

This section presents the results of the shoreline position, beach profile volume, and wave analyses performed to evaluate changes and trends to the beach proximate to the Shoals Club. The Village provided the beach profile survey data as well as orthorectified, historical aerial imagery for the last two decades. Both the beach profile data and aerial imagery have been collected on an annual or bi-annual frequency since 1999 and 2002, respectively. East Beach profile data were only available from 2011 to 2022. Because this study focused on long-term trends over short-term trends, only the annual, summer beach profile survey data were analyzed. All data were converted to the NAD83 horizontal datum and NAVD88 vertical datum when needed to facilitate comparison. The same beach profile station naming convention used in the Olsen monitoring reports was adopted in this study for consistency. Figure 8 depicts the beach profile stations utilized in this report. Table D.1 in Appendix D lists the beach profile station coordinates and azimuths, and Table D.2 lists the survey data available at each station.

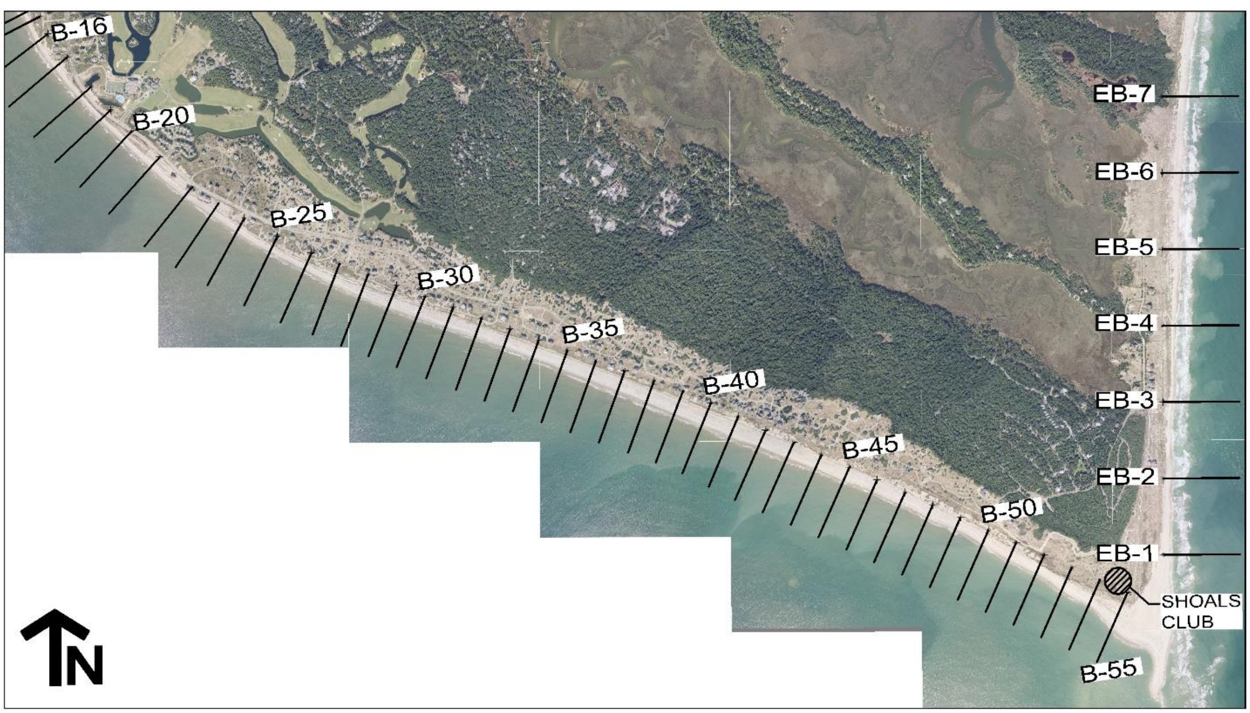

Figure 8: Beach profile station locations and survey azimuths on Bald Head Island. The aerial image was captured in October 2002, prior to the construction of the Shoals Club.

3.1 Historic Aerials

This section discusses the observations around the Shoals Club shorefront based on the aerial imagery obtained from the Village for the past 20 years. The images are a valuable asset to the Village's monitoring program, as they can be used to infer changes along the coast not captured by the beach profile survey data, e.g., Cape Fear point orientation, cross-shoal channel locations through Frying Pan Shoals, wave refraction and breaking patterns. Although the images only depict a snapshot of conditions at the instant the photo was taken, long-term trends can be appropriately discerned. Appendix B.1 and B.2 present the annual aerial imagery at a zoomed out and zoomed in scale, respectively, with the station locations and respective survey azimuths included for reference. Portions of South Beach, East Beach, and Frying Pan Shoals are illustrated in all images.

The most noticeable variation observed through the analysis of the aerial imagery in Appendix B is the configuration of the Cape Fear point, which was consistently oriented to the southeast and as such, the shoreline south of the Club advanced in that direction from October 2002 to May 2007. Thereafter, the point was directed more to the east-southeast while the shoreline south of the Club steadily retreated to the north. Review of historic aerials and shoreline positions from the literature review suggests that the point's more common configuration over the long-term has been an east-southeasterly orientation. There was also a short-term, seasonal component of the point's evolution. The images revealed that during the winter months, the extreme end of the point was often oriented to the south or south-southeast, likely from powerful cold fronts, and during the summer months, it was more often oriented to the east or east-southeast.

In addition to changes in the configuration of the point, the imagery also illustrates intermittent widening of the shoreline along South Beach that resulted from beach renourishment projects, as evident in numerous images (e.g., May 2007, May 2013, Aug. 2015) in Appendix B.1 (zoomed out scale). Typical littoral transport theory predicts the alongshore and cross-shore diffusion (spreading) of the placed beach fill material following a renourishment event. However, the subsequent diffusion of this sand to the east of the project areas is not readily identifiable. Given the assumed sediment transport nodal point identified by Olsen (1989) between beach profile stations B-29 and B-30, it would be expected to observe this spreading of the beach fill material in the aerial imagery as an increase in beach width to the east of the fill areas (towards the Shoals Club shorefront). However, this diffusion signal is not easily identifiable and may only be visible along a 1,000 to 2,000 ft segment east of and adjacent to the fill areas. There were not any recognizable increases in beach width in front of the Club following any of the beach renourishment projects except the 2021 event, and this trend is further supported by the beach profile shoreline position and volume change analyses presented later.

Inspection of the nearshore region within Frying Pany Shoals, just south of the Club, indicates especially dynamic conditions. This region can be characterized as having shallow depths and ephemerally emergent sandbars separated by narrow, east-west directed channels that connect Long Bay to Onslow Bay. The shoals and cross-shoal channels are constantly being reworked and realigned by the forces of waves, winds, and currents. The examination of the aerial photos does not provide evidence that sand located within the Frying Pan Shoals complex has contributed significant sediment to either East Beach or South Beach through onshore migration.

Along the waterline on South Beach, an alongshore current appeared to flow to the east as suggested by the sub-aqueous "overwash" fans at the terminus of the Cape Fear point. This is especially clear in the photos after May 2007 in Appendix B.2 (zoomed in scale). These fans are most evident in the 2014, 2018, and 2020 aerials. Figure 9 illustrates an example of the evidence of an alongshore current and sandbar overwash from the May 2014 aerial image. These strong currents likely increase easterly sediment transport along the beach fronting the Club, resulting in shoreline retreat, as well as prevent the southward progradation of the point. Similar features can be observed in the aerials as a result of strong alongshore currents flowing to the south along East Beach.

Figure 9: Example "overwash" fan at the Cape Fear point from May 2014 aerial.

Lastly, changes in coastal conditions were additionally investigated using Google Earth Engine's Timelapse feature. This webpage provided an animation of annual aerial imagery from 1984 to 2022. Through comparison of the 1998 and 1999 aerials, the orientation of the Cape Fear point was observed to rotate from southeast to south-southwest, and signs of significant dune overwash can also be seen along East Beach as well as the closure of New Inlet (see **Figure 10**). These observations indicate the westerly-directed transport of sand across East Beach, the point, and likely Frying Pan Shoals. During this time period, Hurricane Floyd impacted Bald Head Island and the North Carolina coast as it made landfall near the BHI in September 1999 (NHC, 2014). Hurricanes Denis and Irene additionally produced offshore wave heights in excess of 19 ft during the same season (see **Appendix F.1**). The morphologic changes illustrated in the figure below were likely the result of these three storms. The LIDAR bathymetric map in **Figure C.2** of **Appendix C** provides another view of the reoriented Cape Fear point in October 1999, one month after Hurricane Floyd impacted the area.

Figure 10: Google Engine timelapse imagery illustrating BHI in 1998 (left) and 1999 (right), pre- and post-Hurricane Floyd.

3.2 LIDAR Data Review

The purpose of this review was to evaluate the subaqueous conditions of Frying Pan Shoals just offshore of the Club. As previously mentioned, the shoals in this area are highly dynamic due to the effects of the ever-changing forces of winds, waves, and currents. Light Detection and Ranging (LIDAR) is a technology utilized to collect high-resolution topographic and bathymetric data across wide swaths of area. LIDAR data have been collected on numerous occasions in the vicinity of Bald Head Island, and these data were downloaded from the National Oceanic and Atmospheric Administration's (NOAA) Digital Coast Data Viewer[2]. These data were processed to produce the contoured elevation maps provided in **Appendix C** and span the time period from October 1997 to December 2019.

As evident in some of the maps, LIDAR technology has limitations when collecting elevations in the water column, particularly within the wave-breaking zone and turbid or opaque water bodies like offshore of BHI. Within the Frying Pan Shoals area, the LIDAR data was generally not able to capture accurate depth readings prior to the May 2014 survey, providing no information of the conditions of the shoals. From May 2014 to December 2019, offshore shoals were captured to elevations of approximately -10 ft NAVD88. These maps depict the shoals in various locations during each survey event.

Overall, the infrequency of survey events and the lack of data within Frying Pan Shoals prevent discerning long-term trends in sediment transport pathways and morphological evolution in this area. The maps do, however, provide a reliable snapshot of the topographic features on BHI like MHW shoreline position and the configuration of the Cape Fear point. The conditions of these features were consistent with those presented in **Appendix B.**

3.3 MHW Shoreline Changes

This section summarizes shoreline position changes along the eastern portion of South Beach and the southern portion of East Beach based on the Village's annual, summer survey data. The mean high water (MHW) contour was utilized as a proxy for the shoreline and was taken as +1.41 ft NAVD88 from Olsen (2022a). MHW positions were calculated as a distance measured from the survey station along the survey azimuth (see **Figure 8**). The distances were compared to calculate position changes over time. **Tables D.4** and **D.5** in **Appendix D** list the measured MHW shoreline positions for each survey dataset. Along South Beach, survey data were analyzed from beach profile stations B-16 to B-55 from 1999 to 2022. Along East Beach, survey data was analyzed from beach profile stations EB-1 to EB-7 from 2011 to 2022 (see **Table D.2** for survey data availability).

[2] https://coast.noaa.gov/dataviewer/#/

Figure 11 and **Figure 12** illustrate the cumulative MHW position changes at individual stations along 6,000 ft of East Beach and 4,000 ft of South Beach, respectively, based on available survey data. The y-axis extents vary from station to station, but the scale remains constant to facilitate comparison of position change rates (slopes of the lines). Instances when a beach renourishment event placed sand directly upon the surveyed beach are identified with a vertical orange line. Therefore, these results include the effects of any beach renourishment projects as well as natural erosion and accretion. Note that every other survey station is excluded from the graphic in **Figure 11** in order to cover a wider alongshore extent of beach profiles.

In **Figure 11**, the alongshore variation in the shoreline change is readily evident. The advance or retreat that occurred at the eastern stations was not experienced along the western stations, and vice versa. During the overall monitored time period, the average shoreline position change rates consistently decreased from west to east, with advance of +11.2 ft/yr at B-45 to retreat of -25.6 ft/yr in front of the Club at station B-55. Stations B-45 to B-51 appeared to be stabilized by the direct placement of periodic renourishment material, while stations B-53 to B-55 fluctuated drastically as a result of their proximity to the Cape Fear point.

The growing influence of the Cape Fear point on the MHW shoreline positions is evident in **Figure 11**. From 2005 to 2006, the point shoreline advanced significantly to the south, which caused an updrift, seaward advancement of the shoreline in front of the Club at station B-55 of around 500 ft. By June 2007, this advance continued further updrift to stations B-54 and B-53, which measured advances of approximately 250 ft. The MHW line at station B-51 advanced nearly 200 ft from May 2006 to May 2008; however, the advance at this station may be the result of both the updrift accretion wave as well as a renourishment project in 2007 located 3,000 to 4,000 ft to the west. The significant MHW shoreline advance at these stations was followed by steady shoreline retreat until the most recent survey in May 2022. From May 2008 to May 2022, the MHW shoreline at station B-55 steadily retreated an average of approximately -43 ft/yr.

Figure 12 depicts the cumulative MHW shoreline position changes along East Beach from May 2011 to May 2022. During this time period, the overall shoreline advancement rates increased from north to south, averaging +1.5 ft/yr at station EB-7 to +18.5 ft/yr at station EB-1. Similar to South Beach, the position changes fluctuate drastically with increasing proximity to the Cape Fear point. From station EB-7 to EB-5, the shoreline positions were largely stable to slightly advancing. From station EB-4 to EB-1, the MHW shorelines steadily advanced from May 2011 to May 2019. From 2019 to 2020, the figure reveals a substantial retreat event occurred at stations EB-1 and EB-2 of -400 ft and -140 ft, respectively. This occurrence was likely related to the passing of Hurricane Dorian in September 2019. Thereafter, a south to north “wave” of shoreline recovery (advance) appeared to occur at station EB-1 and two years later at stations EB-2 and EB-3.

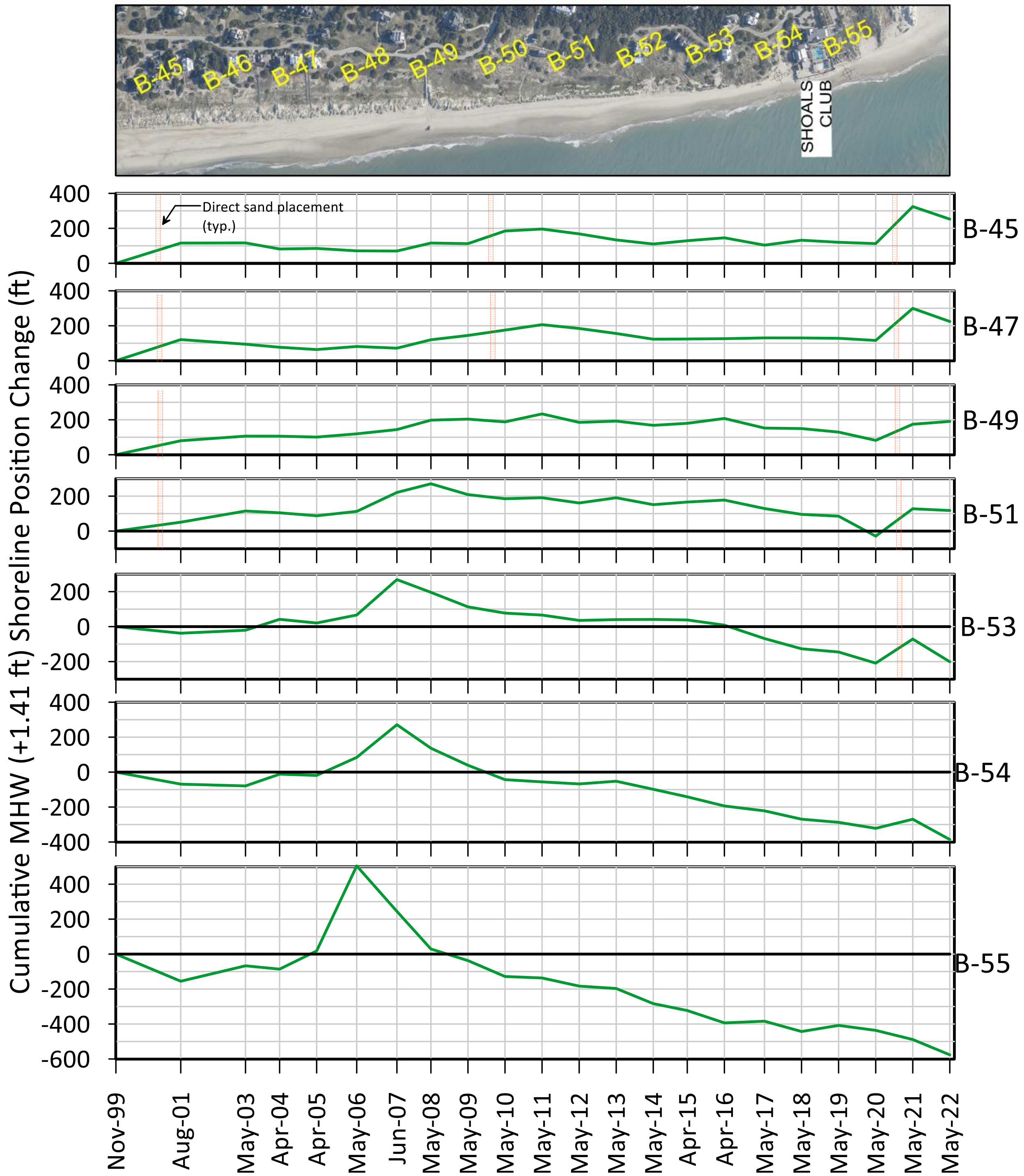

Figure 11: Cumulative MHW (+1.41 ft NAVD88) shoreline position change (ft) along South Beach stations B-45 to B-55 from November 1999 to May 2022.

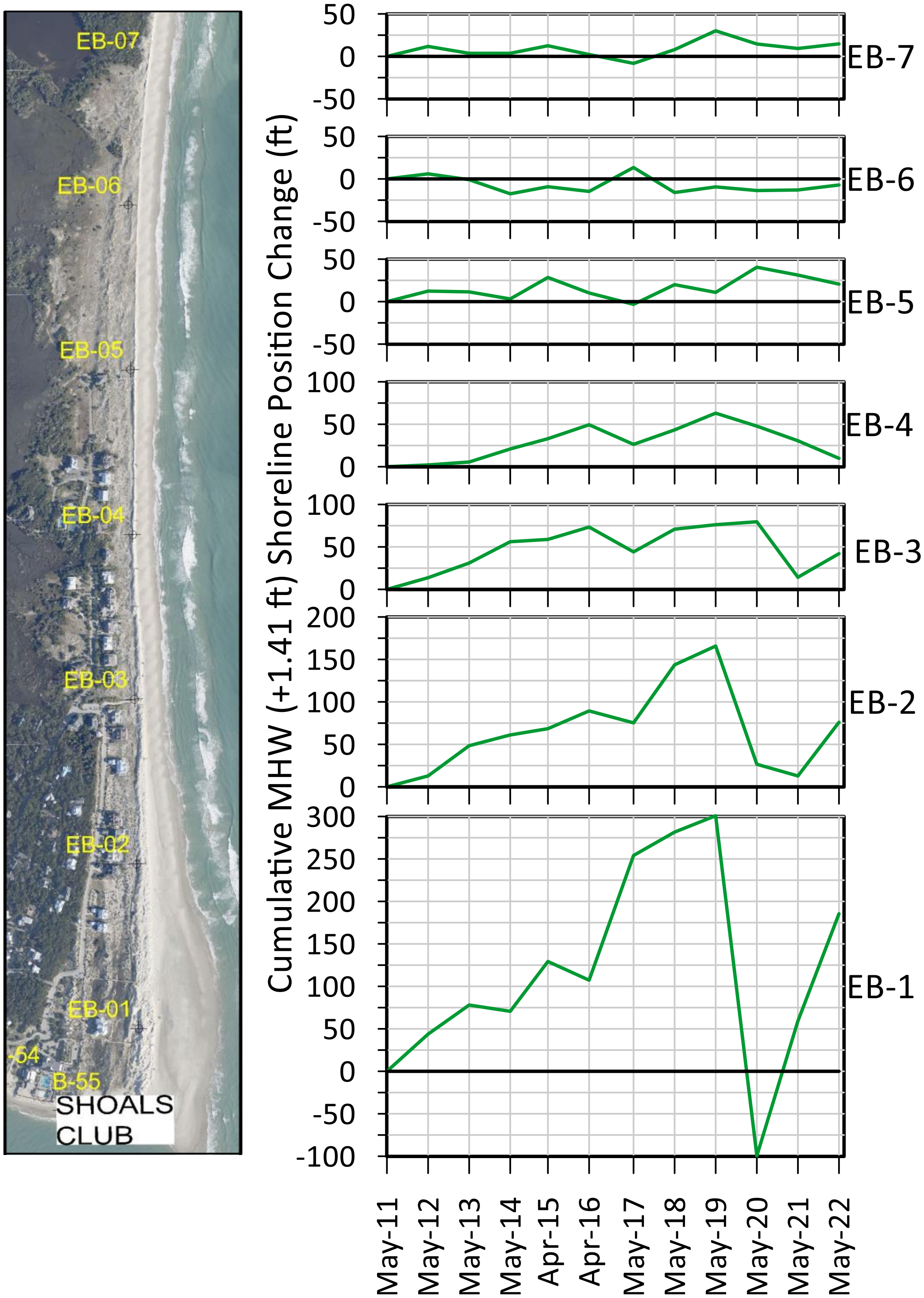

Figure 12: Cumulative MHW (+1.41 ft NAVD88) shoreline position change (ft) along East Beach stations EB-1 to EB-7 from May 2011 to May 2022.

In general, comparison of shoreline change trends along southern East Beach and eastern South Beach indicate an inverse relationship of advance and retreat during the past ten years from May

2011 to May 2022. In general, when southern East Beach was advancing, eastern South Beach was retreating. This relationship appears to result from the configuration of the Cape Fear point acting as a barrier to littoral drift (i.e., south-directed spit acts as barrier to South Beach and east-directed spit acts as barrier to East Beach).

Figure 13 presents historic shoreline positions along East and South Beach from 1855 to October 2022. The shorelines from 1855 to 1996 were digitized from the *Final Environmental Impact Statement* (USACE, 2014). The depicted shoreline positions following 1996 represent the MHW contour based on the Village's beach profile survey data.

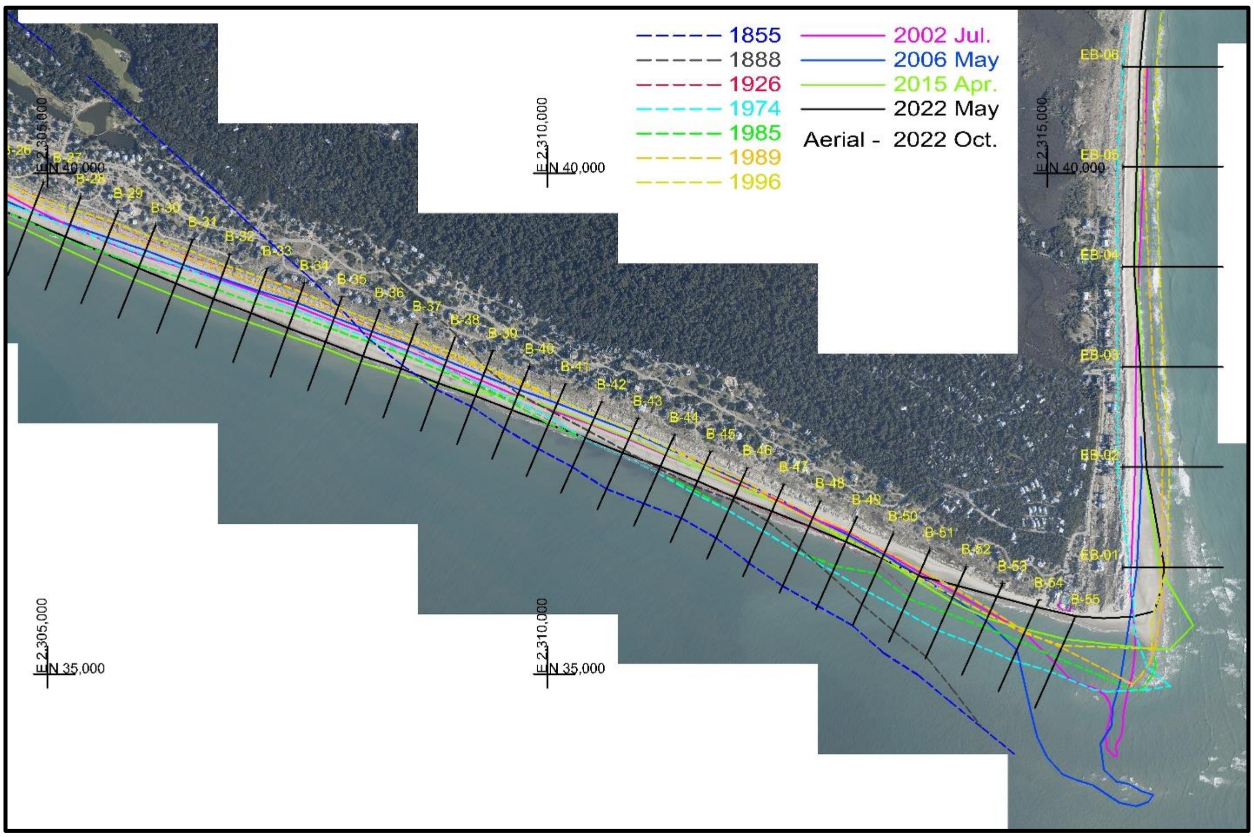

Figure 13: Historic shoreline positions from 1855 to October 2022.

The South Beach historic shorelines in the vicinity of the Club demonstrate an overall trend of retreat since the earliest 1855 position. Within this overall period, however, there were periods of substantial retreat as well as advance. From 1855 to 1926, eastern South Beach retreated hundreds of feet. The available shoreline positions suggest a seaward rebound of the shoreline between 1926 and 1974. From 1974 to 1996, there was steady but relatively moderate shoreline retreat. From 1996 to 2002, during which Hurricane Floyd impacted BHI in September 1999, the southward development of the point can be observed, followed by substantial southward advance by 2006. **Figure 11** summarizes shoreline position changes following the advance leading to the

2006 position. Shoreline positions along East Beach varied as well during the time period illustrated in **Figure 13**, though to a much lesser extent.

3.4 Volume Changes

This section describes the analyses and results of the beach profile volume changes based on the annual summer survey data provided by the Village. The data limits extend from landward of the dunes, to 3,000 to 4,000 ft offshore. The South Beach coastline was analyzed from B-16, roughly 1,000 ft east of the terminal groin, to B-55, adjacent to the Club during the time period from November 1999 to May 2022. East Beach data was analyzed from May 2011 to May 2022 along the 6,000 ft of shoreline from EB-1 to EB-7.

Offshore volume calculation limits were imposed to focus the analyses on changes to the beach profile within the estimated depth of closure. The depth of closure is the offshore limit beyond which there is no significant change in elevation of a beach profile. For this study, the depth of closure was estimated by visually comparing the beach profiles and selecting the appropriate distance offshore where elevation change was minimal. Additional care was taken to select offshore limits that were not substantially different from the adjacent beach profiles so as to avoid volume change results unequally influenced by varying calculation widths. The selected depth of closure/offshore volume calculation limits are depicted on the beach profile plots in **Appendix A** and tabulated in **Table D.3** of **Appendix D**.

Consecutive surveys were compared to calculate the volume density changes at each analyzed station above the MHW and DOC reference datums. Note that the calculated densities were not adjusted for beach renourishment volumes. **Figure 14** presents the volume density changes along South Beach during three different time periods of around seven years in duration: November 1999 to June 2007, June 2007 to April 2015, and April 2015 to May 2022 representing the time periods of southward growth of the Cape Fear point, the retreat of the point, and the most recent time period, respectively. The orange and blue bars represent the volume changes above the MHW and DOC datums respectively; therefore, the changes above DOC encompass the changes above MHW.

Inspection of the volume density changes along the eastern 2,000 ft of South Beach from stations B-50 to B-55 in **Figure 14** indicates that the earliest time period (upper plot), when the point was advancing to the south, experienced broad accretion above both the MHW and DOC datums. Within the same segment of beach during the following time period from 2007 to 2015 (central plot), only the three eastern South Beach profiles from station B-53 to B-55 experienced erosion. During the most recent time period (lower plot), the easternmost 2,000 ft of beach experienced substantial erosion above and below the MHW line. During the 15 years from 2007 to 2022, the erosion along the eastern end of South Beach moved westward (updrift) from the point. Most notably, the beach profile adjacent to the Club (B-55) eroded approximately -112 cy/ft above MHW and -216 cy/ft above the DOC during the seven-year period from 2015 to 2022.

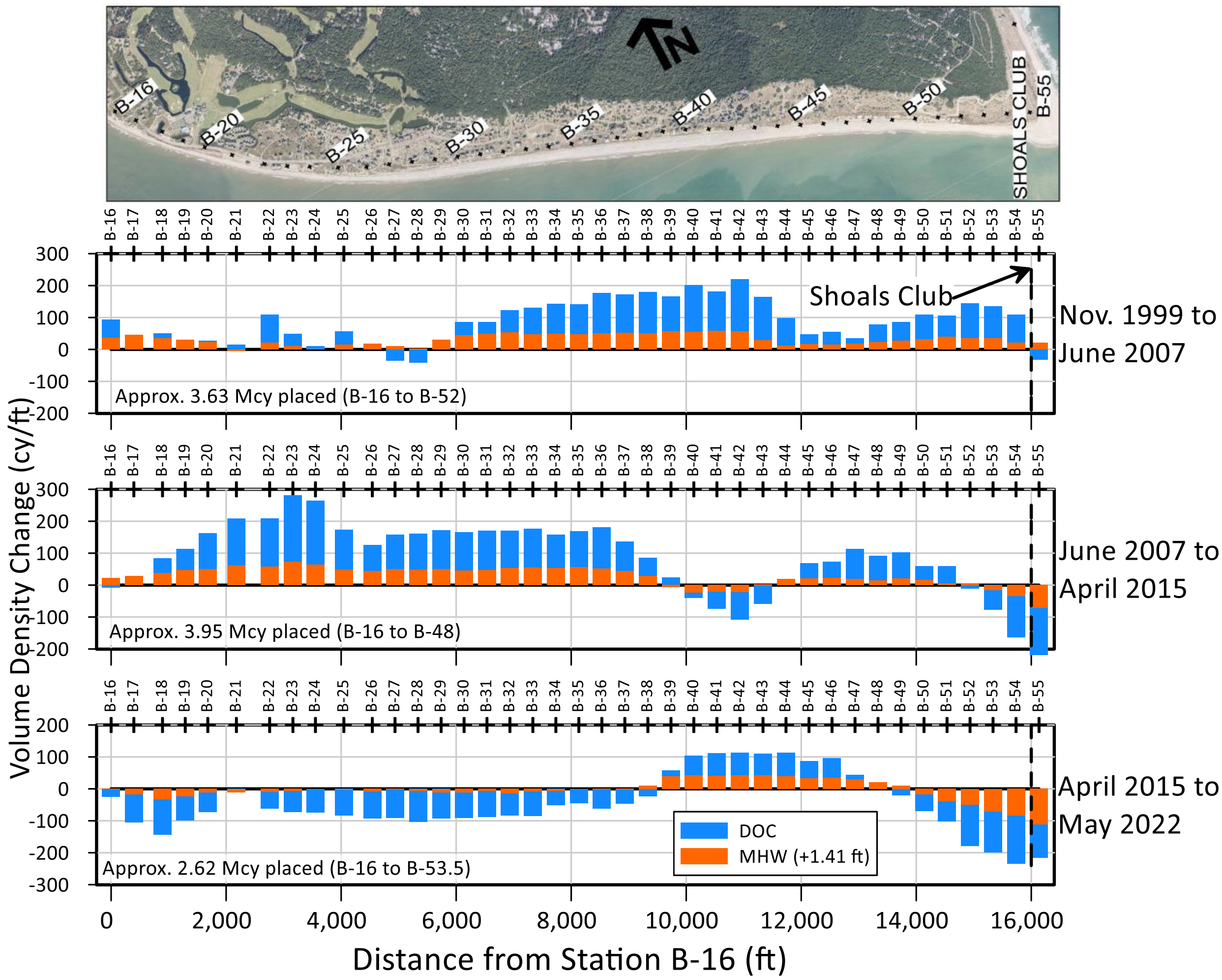

Figure 14: Volume density changes along South Beach from during three different time periods above MHW (+1.41 ft NAVD88) and the depth of closure (DOC).

Appendix E presents each consecutive volume density change graphic from 1999 to 2022 along South Beach and from 2011 to 2022 along East Beach. Along South Beach, the graphics illustrate the influence that the periodic beach renourishment projects have on the western two-thirds of the shoreline. The volume densities of the beach profiles along the eastern third of the shoreline fluctuated on a year-to-year basis without any identifiable spatial trend, with some years slightly erosional to accretional, and other years highly erosional or accretional. Above MHW, values generally ranged between ±20 cy/ft, while the volume densities within the DOC generally ranged from ±50 cy/ft. Along East Beach, the graphics illustrate similar levels of spatial and temporal fluctuation.

Volume changes were also calculated using the average-end area method utilizing the volume densities previously described and the distances between adjacent beach profile stations. **Figure 15** presents the cumulative volume changes above the DOC line along different lengths of beach west of the Club from 1999 to 2022. The various lines represent different lengths of beach, as listed in the legend; therefore, they should not be directly compared. The orange vertical lines signify the placement of beach fill along the shorelines named next to the vertical lines. Note that fill was not necessarily placed within each analyzed segment of beach during the renourishment projects. For example, the second renourishment event that occurred in 2005 did not place fill in any of the analyzed beach segments.

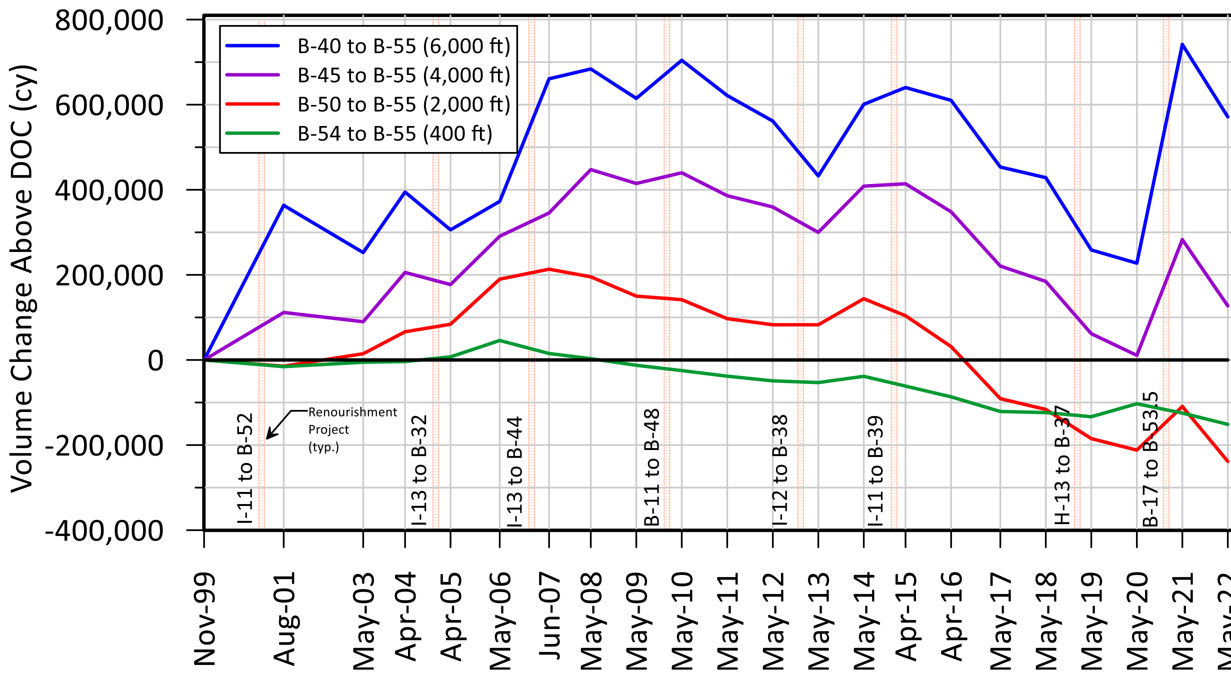

Figure 15: Cumulative volume change above the DOC datum along various sections of South Beach from 1999 to 2022. The beach profile stations beginning with I and H are located along West Beach, outside of the study area in this report.

As the figure demonstrates, the 400 ft of beach in front of the Club above the DOC between stations B-54 to B-55 (green line) was relatively stable from November 1999 to May 2008. The broader shoreline segments to the west of the Club increased in volume during this time period due to the effects of direct placement of sand from renourishment projects as well as an overall accretional trend, perhaps from the diffusion of updrift placed sands and the southerly orientation of the Cape Fear point. As discussed in the previous section, the southerly orientation of the point acts as a barrier to easterly directed littoral transport on eastern South Beach, which ultimately led to the temporary accretion experienced along the Club's shorefront during this time period.

From May 2008 to May 2022 and between stations B-54 and B-55, approximately -151,300 cy were steadily lost above the DOC datum, or at a rate of approximately -11,000 cy/yr. The addition of sand from the beach renourishment projects during this time period did not result in appreciable accretion in front of the Club. The three broader shoreline segments eroded at a higher rate during this same time period but were partially mitigated by the 2021 renourishment project. Note that during this time period, the Cape Fear point had been oriented in a more easterly direction for several years and was steadily retreating to the north.

Figure 16 illustrates the cumulative volume changes, adjusted for beach fill volumes, above the DOC datum along various lengths of beach west of the Club from 1999 to 2022. With the fill volumes removed, the background erosion and accretion trends are more readily identifiable. The volume changes along the 400 ft of beach between stations B-54 and B-55 (green line) are equivalent to those in the previous figure because no fill was placed in this area. Also similar to the previous figure, the period from May 2003 to May 2008 was net accretional along the various beach segments due to the southerly orientation of the point. From early 2007 to May 2022, the point was generally retreating to the north and in an easterly configuration, which allowed easterly transported sediment along South Beach to flow, unobstructed, to the terminus of the point and eventually into Frying Pan Shoals. Therefore, during this time period, there was nearly steady erosion along each segment except for during the 2013 to 2014 time period.

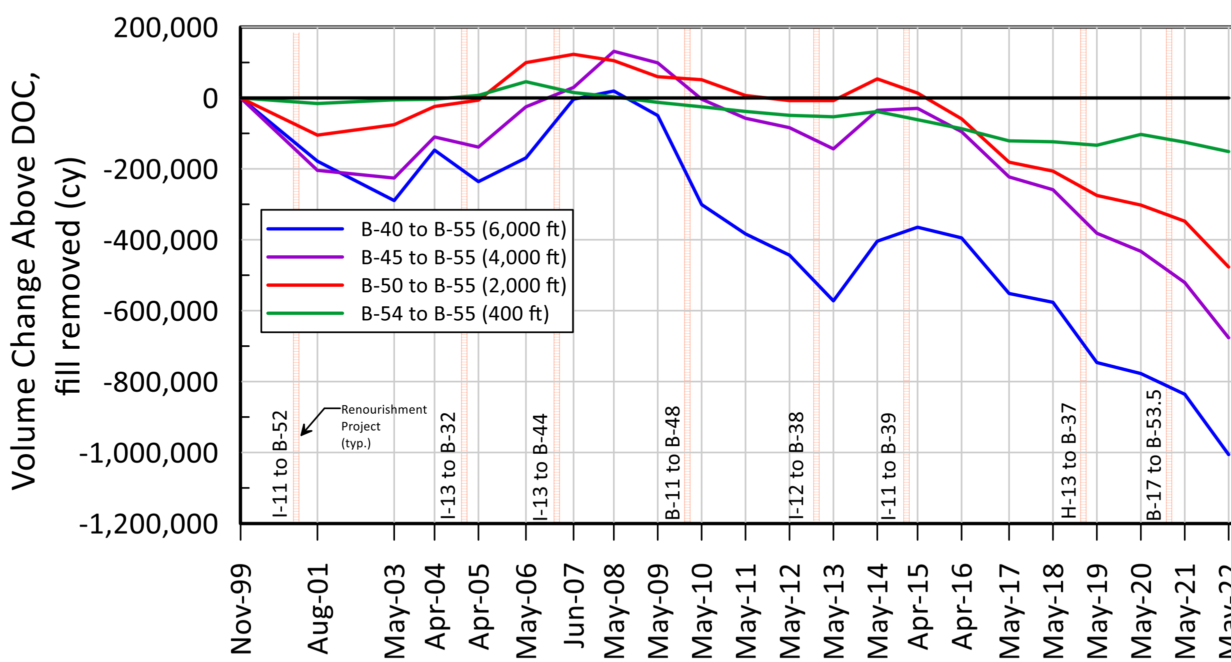

Figure 16: Cumulative volume change with fill volumes removed above the depth of closure (D)C) along various sections of South Beach from 1999 to 2022.

Overall, **Figure 15** and **Figure 16** demonstrate the link between the orientation of the Cape Fear point and the overall erosional or accretional trends experienced along eastern South Beach. When the point was oriented to the south, easterly transported sediment was captured by the point, acting as a littoral barrier, and the beaches accreted. When the point was oriented more to the east, the littoral barrier effect for South Beach did not exist. South Beach sediments were transported to the east and flowed, unobstructed, to the terminus of the point, resulting in erosion along the Club's shorefront. Additionally, the graphics illustrate that the various beach renourishment projects did not mitigate the erosion experienced along the beach in front of the Club.

The cumulative volume changes along segments of East Beach from May 2011 to May 2022 are depicted in **Figure 17**. Changes above the DOC are on the left, and changes above MHW are on the right. Throughout this time period, the Cape Fear point was generally more easterly oriented and retreating northward. Note that East Beach was impacted by the passing of Hurricane Dorian in September 2019.

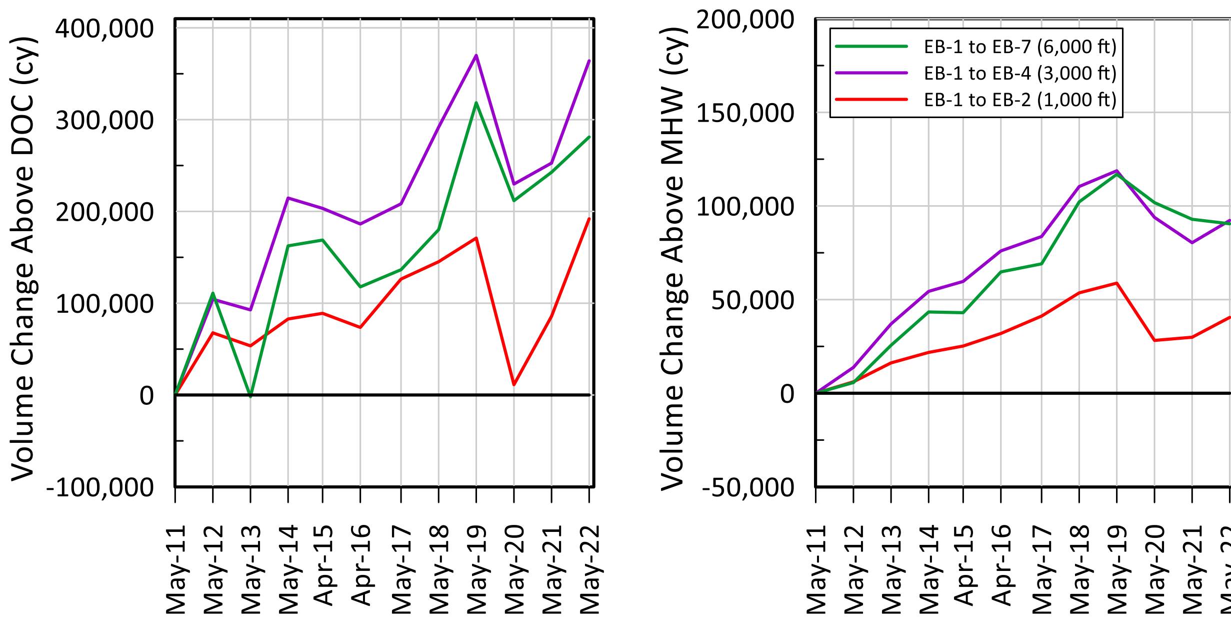

Figure 17: Cumulative volume change above the depth of closure (DOC, left) and MHW (right) datums along various sections of East Beach from 2011 to 2022.

Similar to the results along South Beach, the volume changes along East Beach varied substantially from north to south as a result of the influence of the Cape Fear point. It is observed in **Figure 17** that the entire 6,000 ft segment from EB-1 to EB-7 (green line) gained approximately 281,000 cy above DOC and 90,000 cy above MHW, or approximate rates of 28,000 cy/yr and 9,000 cy/yr, respectively. The southernmost 1,000 ft segment (red line) comprises approximately 45% of this total accretion above MHW and 68% above the DOC. As discussed in the previous section, the easterly orientation of the point acted as a littoral barrier to southerly transported sediments along East Beach. The littoral barrier captured sediment, resulting in accretion updrift (north) of the point. This barrier effect/accretion signal increases with increasing proximity to the point, and the results presented below are consistent with this observation.

Figure 18 presents the annualized, cumulative volume change rates above the DOC along South Beach during four periods of interest between 1999 to 2022. The calculated volume changes were adjusted to remove the effects of placed sand due to a renourishment project, when necessary. Volume changes during each time period were summed cumulatively beginning at the approximate nodal area identified in Olsen (1989), where the net sediment transport diverges. This area is marked with the vertical dashed line at station B-29 in **Figure 18**. The cumulative addition of volume changes facilitates discerning spatial trends in erosion and accretion in the figure. Between the nodal area and the Club, erosion is evidenced by a negative slope (directed down and to the right), accretion by a positive slope (directed up and to the right), and a stable shoreline is horizontal.

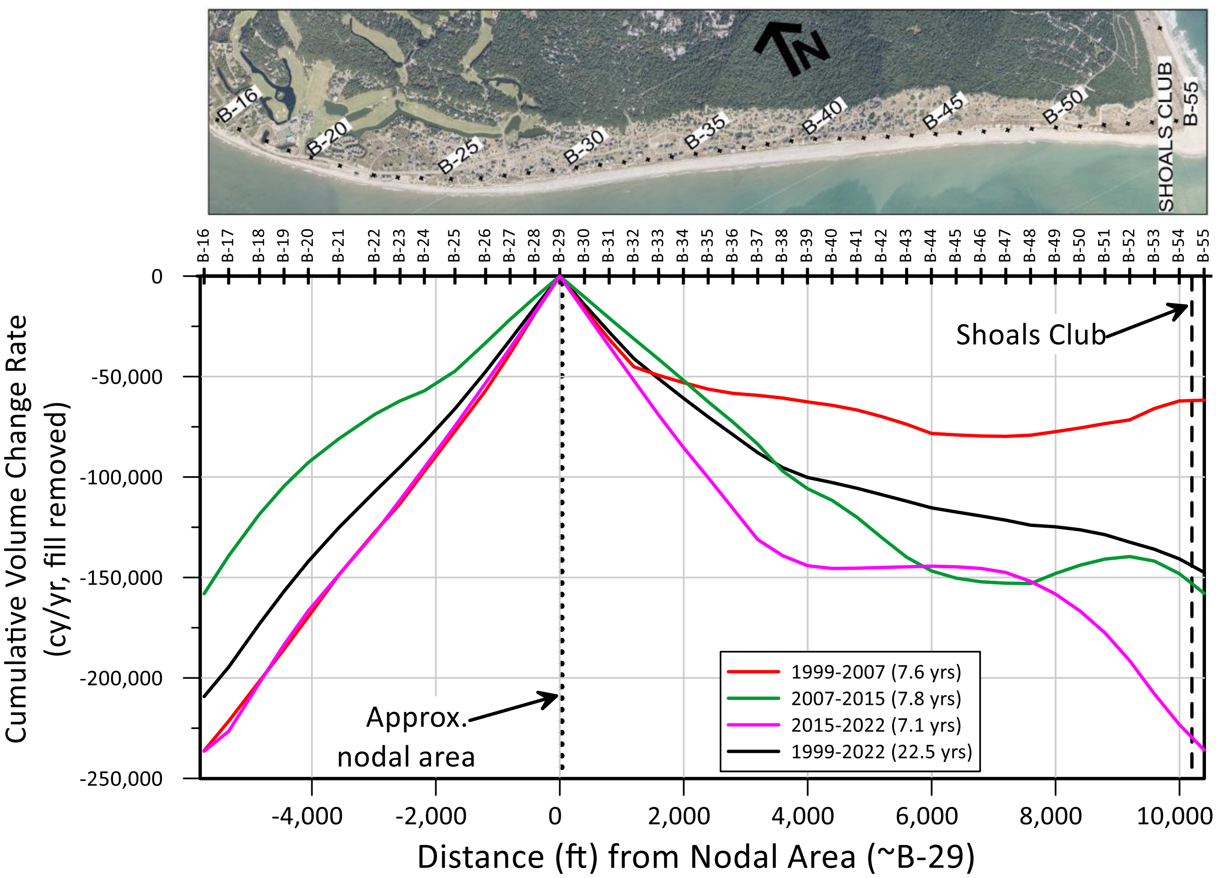

Figure 18: Cumulative volume changes rates above the depth of closure with beach fill volumes removed for various time periods from 1999 to 2022 along South Beach, relative to the nodal area.

The 7.6 years from November 1999 to June 2007 (red line) represents the time period when the Cape Fear point was oriented to the south, stabilizing eastern South Beach. The 7.8 years from June 2007 to April 2015 (green line) represents the time period that the point began to reorient to the east and the shoreline gradually retreated to the north. The 7.1 years from April 2015 to May 2022 (magenta line) represents the most recent time period when the Club infrastructure began to be threatened with ongoing beach erosion. The entire 22.5-year period from November 1999 to May 2022 is illustrated by the black line in the figure.

During the earliest time period from 1999 to 2007, when the point was oriented to the south, the shoreline from the nodal area to the Club experienced net erosion at an average annual rate of -61,700 cy/yr. Within that segment however, the easternmost 3,200 ft from B-47 to B-55 accreted at an average annual rate of 18,000 cy/yr, or 5.6 cy/ft/yr on average. Compared to the other time periods presented in the figure, this earliest time period corresponds to the highest stability (least erosional) of the beaches east of the nodal area.

From 2007 to 2015, when the point reoriented to the east and gradually began retreating to the north, the 6,000 ft from B-29 to B-44 eroded at an average annual rate of approximately -150,000 cy/yr, or -25 cy/ft/yr. The 2,000 ft to the east from B-44 to B-49 was more or less stable. The easternmost 2,400 ft of beach from B-49 to B-55 experienced both accretion (+7.1 cy/ft/yr) along the western half and erosion (-15.2 cy/ft/yr) along the eastern half. As the point oriented to the east and began retreating to the north, the littoral barrier effect of the point diminished, allowing easterly-directed transport (erosion) of the previously accumulated sand into Frying Pan Shoals. This erosion signal traveled west (updrift) from the point during this time period but only reached to around B-52 (around 1,200 ft to the west of the Club) as indicated in the figure.

The most recent period from 2015 to 2022 (magenta line) represents the most erosional time period in the figure. The segment of beach from the nodal area to B-39 eroded approximately -36.1 cy/ft/yr, on average. This elevated erosion may have provided the necessary sediment supply to the 3,200 ft of beach to the east from B-39 to B-47, which was more or less stable during this time period. The easternmost 2,000 ft of beach from B-50 to B-55 experienced the worst erosion during this time period relative to the previous 16 years, with an average annual loss of approximately -69,100 cy/yr, or -34.6 cy/ft/yr. During this time period, the point had been oriented to the east for several years, and the erosional wave induced by the reorientation of the point (described in the previous paragraph) had traveled further to the west from B-52 to around B-47 or B-48. This phenomenon ultimately resulted in the increased erosion rates experienced along the Club's shorefront during this time period.

A similar analysis was conducted along East Beach with the available survey data from May 2011 to May 2022. Volumes were summed from north to south beginning at EB-7. There were no beach renourishment projects along East Beach during this time period, so volume changes were not adjusted. **Figure 19** presents the annualized cumulative volume change rates along East Beach during the four-year period from May 2011 to April 2015, the seven-year period from April 2015 to May 2022, and the overall 11-year period from May 2011 to May 2022.

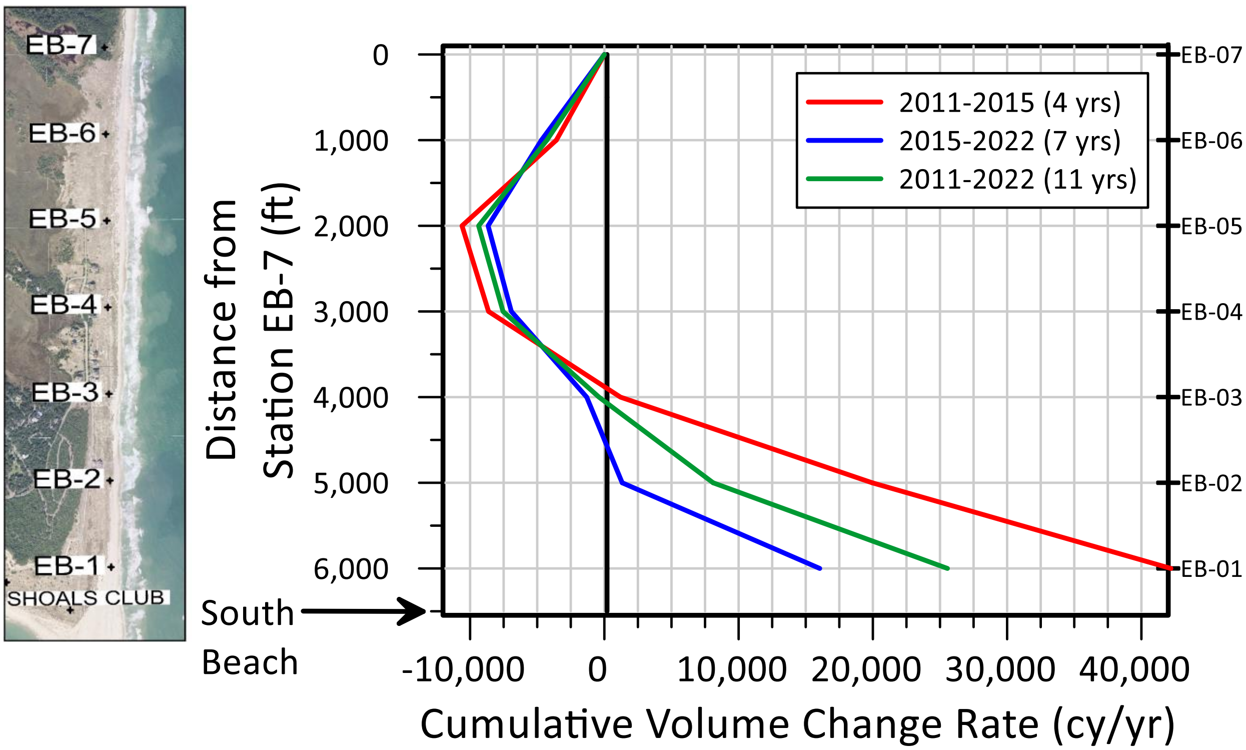

Figure 19: Cumulative volume changes rates above the depth of closure for various time periods from 2011 to 2022 along East Beach.

Compared to **Figure 18**, the axes on the figure above have been switched to reflect the change in orientation of the coastline along East Beach. Therefore, in **Figure 19**, regional accretion is evidenced by a downward-right slope in the lines and erosion is evidenced by a downward-left slope.

As evidenced by the similarity in the lines north of EB-3, there was little variation in the volume change trends during the different time periods in this segment of beach. The northernmost 2,000 ft of beach (EB-7 to EB-5) consistently eroded on the order of -10,000 cy/yr, or -5 cy/ft/yr on average, whereas the 2,000 ft of beach to the south from EB-5 to EB-3 increased in volume at a similar rate. The southernmost 2,000 ft of beach was highly accretional during each time period. The four years from 2011 to 2015 experienced the highest rate of accretion in this segment, around 21 cy/ft/yr on average, as a result of the littoral barrier effect induced by the easterly orientation of the point. During the following seven years from 2015 to 2022, this segment continued to increase in volume, albeit at a slower average rate of 8.7 cy/ft/yr. Overall, the accretion experienced along East Beach during the various time periods was a direct result of the easterly orientation of the point acting as a littoral barrier to the southerly transported sands along East Beach.

3.5 Wave Analysis

This section details the investigation of the contemporary wave climate and its relationship to the Cape Fear coastline through a combination of wave climate analysis and numerical modeling. The primary goal of the wave climate analysis was to determine if particular changes in the recent wave climate and/or particular offshore features were responsible for the erosion that impacted the Club during the last decade and a half. The wave climate analysis was conducted to identify annual variability and changes in the wave climate that may have led to the variable shoreline and volume changes discussed in the preceding sections. Additionally, numerical modeling was employed to simulate typical wave conditions as well as conditions during specific storms. The modeling results identify complex wave propagation, transformation, and refraction patterns across the study area.

3.5.1 Wave Climate

As previously mentioned, the primary goal of this portion of the study was to determine if particular changes in the recent wave climate and/or particular offshore features are responsible for the erosion that has impacted the Club during the last decade and a half. To that end, offshore wave data were downloaded and analyzed for trends. There are numerous publicly available wave data sources offshore of BHI from nearby NOAA buoys and the USACE Wave Information Study (WIS). Both wave data sources were investigated to determine the most appropriate source for the analysis of wave data variability. The NOAA buoys provide real-time measurements, while the WIS wave data are calculated from hindcast wind measurements. Ultimately, the WIS data were selected for analysis because they provided a longer duration of wave data to analyze and did not contain any gaps in data, unlike the NOAA datasets.

The hindcast wave data were downloaded from the WIS catalog (WIS, 2023) and contained significant wave height, peak wave period, and peak wave direction values at hourly intervals from January 1980 to December 2021. Data from three different WIS stations (see **Figure 20**) were utilized in this study:

- Station 63309: located 17 miles southwest of the Club at a depth of 62 ft,

- Station 63320: located 26 miles southeast of the Club at a depth of 78 ft, and
- Station 63509: located 61 miles southeast of the Club at a depth of 700 ft.

A ranking of extreme wave events was downloaded from the WIS website for Station 63309. This station is located closest to BHI and within the influence of Frying Pan Shoals, thus is more representative of nearshore wave conditions along South Beach and the Club's shorefront. The wave analysis portion of the study (present section) utilized the wave data hindcasted from Station 63320 in order to investigate wave properties along the outer rim of Frying Pan Shoals. The waves from this station are considered more representative of nearshore conditions along both East Beach and South Beach than the offshore Station 63509. Lastly, the numerical modeling portion of the study (described in next section) utilized the wave data hindcasted from Station 63509 in order to enable the wave model to transform deep water waves to the nearshore.

Figure 20: Locations of WIS Stations 63309, 63320, and 63509.

Figure 21 depicts the directional wave statistics (height, direction, and frequency of occurrence) derived from the 1980 to 2021 WIS Station 63320 data record. The figure indicates that during the 42-year record, the majority of waves originated from the southeast direction with wave heights between two and four feet. Waves with heights between four and six feet were represented from all directions with a similar frequency of occurrence. Waves from six to eight feet in height most frequently came from the east-northeast and are most likely associated with winter season nor'easters. The greatest wave heights originated from the south and southeast, which are primarily associated with tropical storms and hurricanes.

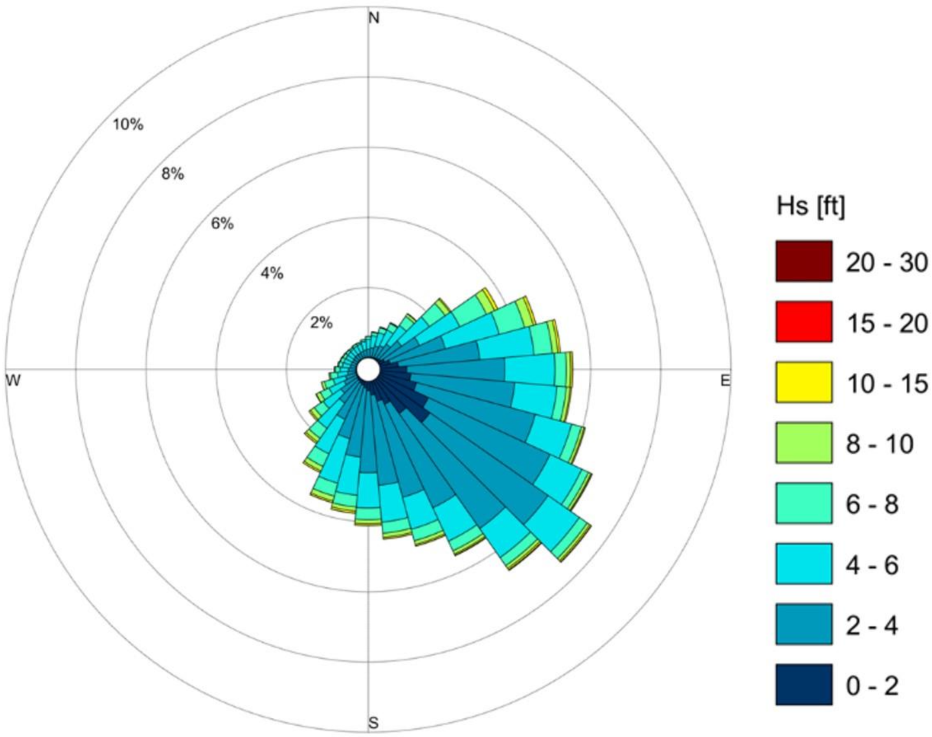

Figure 21: Directional wave statistics from WIS Station 63320 from January 1980 to December 2021.

Figure 22 presents the seasonality of the directional wave statistics at WIS Station 63320 derived from the 1980 to 2021 data record for the summer (April through September) and winter (November through March) seasons. The summer/winter seasonality of the wave climate along the North Carolina coastline has been responsible for the periodic oscillation of the extreme tip of the Cape Fear point, which can be reviewed in the aerials in **Appendix B**. Winter months exhibited higher wave heights more frequently and predominantly originated from the east-northeast and east-southeast. The average wave height for the winter months was 4.6 ft.

The summer season is characterized by smaller waves arriving predominantly from the southeast direction. On average, the wave height during the summer months was 3.9 ft. Summer conditions can be episodically affected by the passage of tropical systems (i.e., hurricanes and tropical storms) originating from both the Atlantic Ocean and the Gulf of Mexico. Hurricanes and tropical storms can bring extreme winds, waves, and storm surge, which can cause significant morphological changes in coastal areas in a very short period of time. The impacts of these systems can be severe and can be influenced by the system's size, intensity, proximity, path, and forward speed in relation to an area. **Figure 23** illustrates the historic tracks of hurricanes that came within 30 miles of the Shoals Club between 1980 and 2022. Hurricanes Fran (1996), Bertha (1996), and Floyd (1999) all made landfall on BHI as a Category 2 storm or greater.

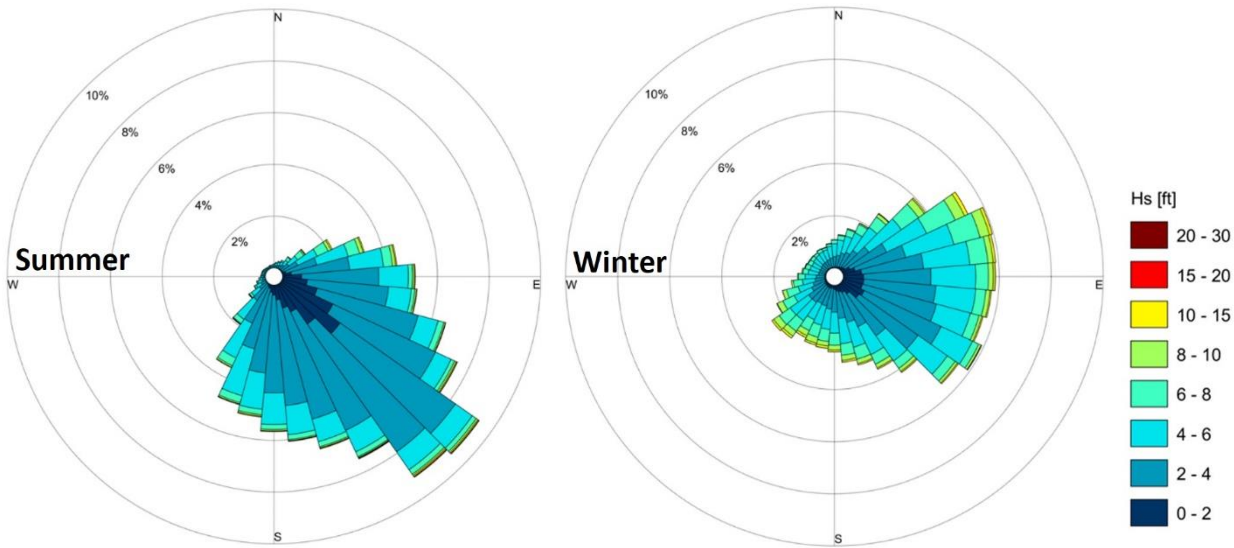

Figure 22: Directional wave statistics from WIS Station 63320 from January 1980 to December 2021 for summer (left, April through September) and winter (right, November through March).

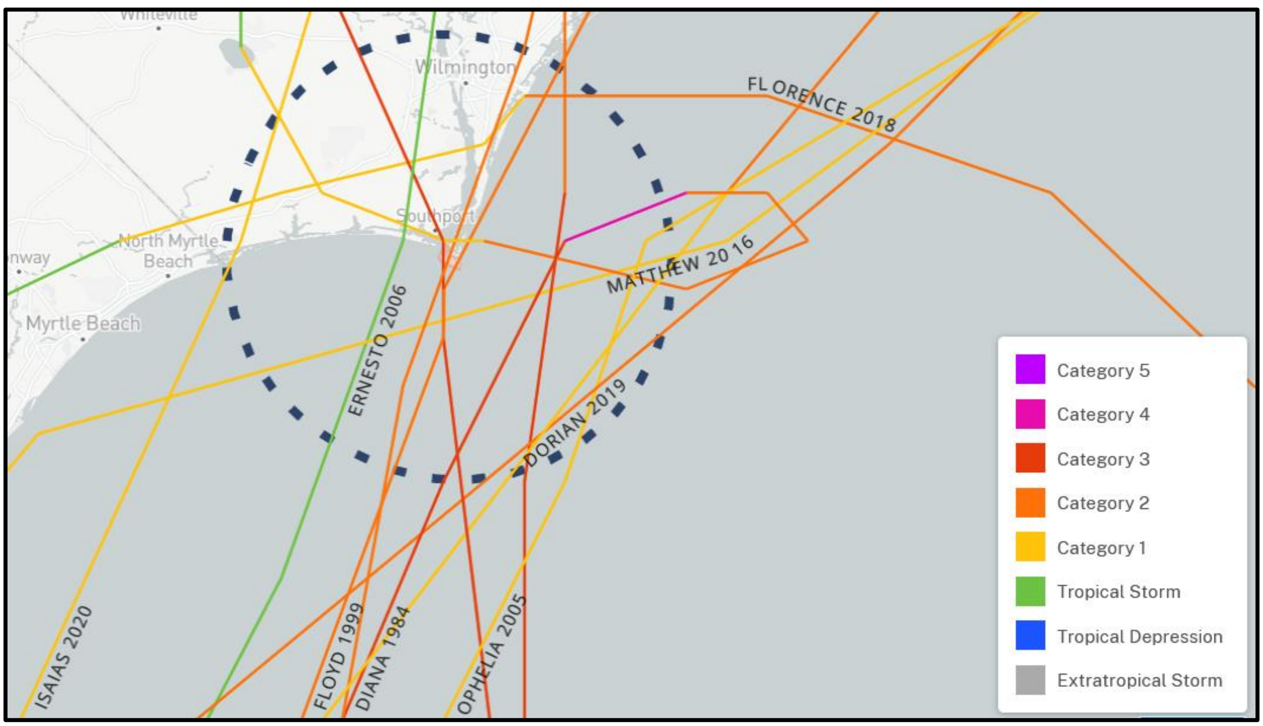

Figure 23: Hurricane tracks within 30 miles of the Shoals Club between 1980 and 2022. Reproduced from https://coast.noaa.gov/hurricanes.

The highest ten significant wave height events hindcasted with the 42-year WIS record from Station 63309 are listed in **Table 2**. All events were associated with the passing of a hurricane except the "Storm of the Century," which occurred in March 1993.

Table 2: The highest ten significant wave height events hindcasted with the 42-year (1980-2021) record from WIS Station 63309.

Event	Date	Significant Wave Height [ft]	Significant Wave Period [s]	Mean Wave Direction [deg]	Associated Storm
1	Sept. 2008	20.0	14.1	168.2	Hurricane Hanna
2	Sept. 1999	19.7	15.8	136.3	Hurricane Floyd
3	Sept. 1989	19.0	14.9	149.2	Hurricane Hugo
4	Mar. 1993	19.0	13.1	206.5	"Storm of the Century"
5	Sept. 2019	18.4	13.0	144.9	Hurricane Dorian
6	Sept. 1996	18.4	15.7	108.3	Hurricane Fran
7	Jul. 1996	18.0	14.0	128.2	Hurricane Bertha
8	Aug. 2020	18.0	12.0	177.2	Hurricane Isaias
9	Aug. 1998	17.7	15.1	100.8	Hurricane Bonnie
10	Oct. 2016	17.4	12.8	173.0	Hurricane Matthew

Variations in the annual wave climate were also evaluated on a year-to-year basis from 1999 to 2021 utilizing the wave data from WIS Station 63320. The annual wave data were grouped from May to May of the following year to correspond with the shoreline position and beach profile volume change time periods described in the previous sections. The yearly, May-to-May average, modal, and maximum wave heights and directions are presented in **Figure 24**. **Appendix F.1** includes the May-to-May wave height records and corresponding wave roses, along with various statistics and hurricane tracks for reference.

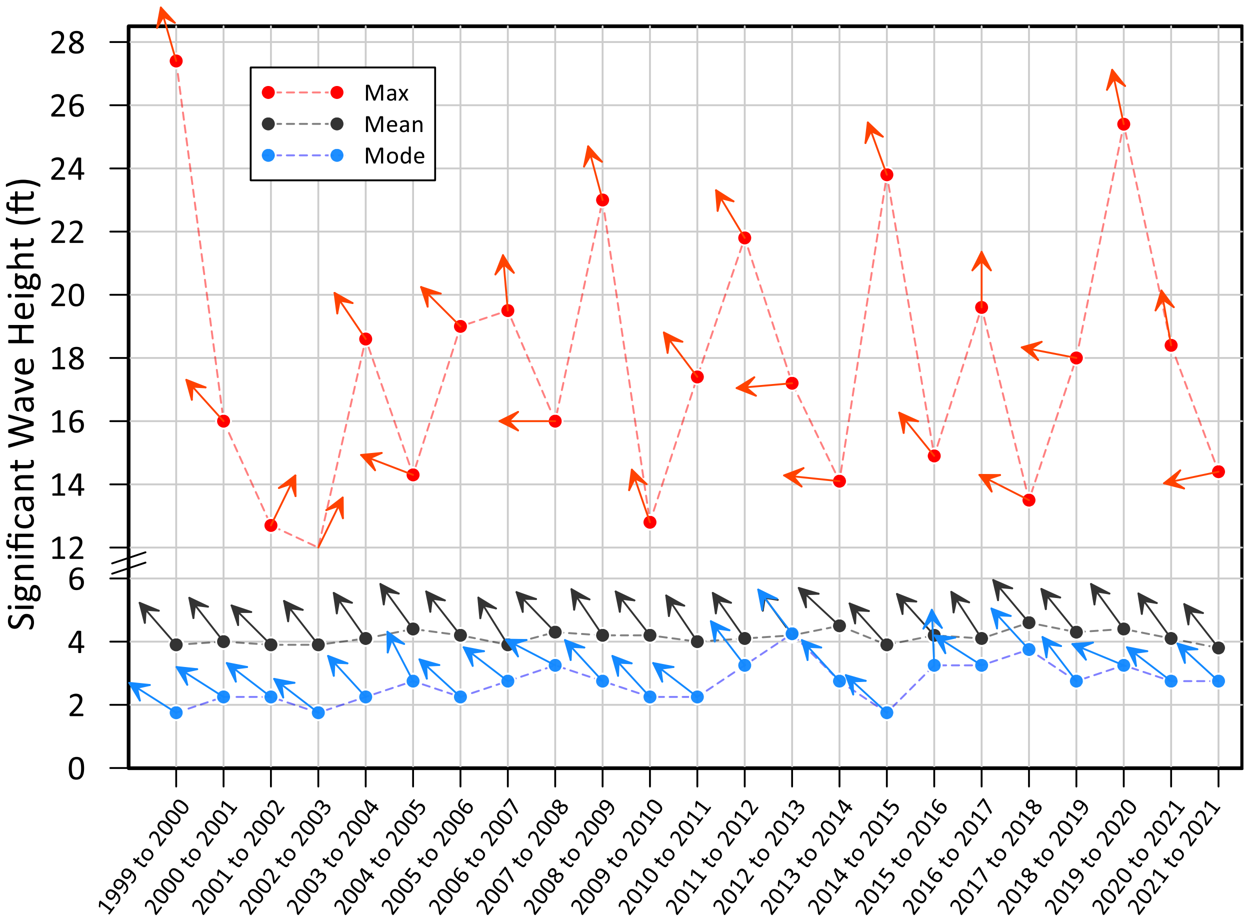

Figure 24: Yearly, May-to-May wave height and direction statistics from 1999 to 2021 for WIS Station 63320.

The modal values in the figure represent the most frequently occurring wave heights and directions. The high energy events, depicted by the maximum wave heights in the figure, had the greatest potential to promote significant morphological changes along the shoreline in a relatively short period. The average and modal waves illustrate the more typical annual wave conditions which have the ability to gradually influence morphological change.

Review of the figure indicates that the average significant wave height generally fluctuated by about 0.5 ft during the 22-year wave record and ranged from 3.8 to 4.6 ft. The average direction was consistently from the southeast. The modal wave height ranged from around 2 ft to 4 ft and increased on the order of 1 ft throughout the duration of the wave record. The modal wave direction was consistently from the southeast, though it comprised a slightly more eastern direction than the average directions. The maximum wave heights ranged from 12 ft to 27.4 ft, with directions varying from east to south-southwest. All of the events with significant wave heights greater than 20 ft originated from the south-southeast and have occurred every three to five years since 2008.

The percentage of waves greater than 8 ft during each monitoring year is illustrated in **Figure 25**. These waves comprised between approximately 2.5% and 8% of all waves during the 21-year wave record, and on average, they comprised approximately 4.5%. The figure indicates that the 2-yr period from summer 2004 to summer 2006 as well as the 4-yr period from summer 2017 to summer 2021 experienced an above average frequency of wave conditions greater than 8 ft. In contrast, the 3-yr period from summer 2001 to summer 2004 was characterized by below average frequency of elevated wave conditions. During the past decade, eight of the years experienced above average frequency of elevated wave conditions. Overall, there is not a strong link between the cumulative volume change rates along South Beach in **Figure 18** and the wave climate illustrated in **Figure 24** and **Figure 25**.

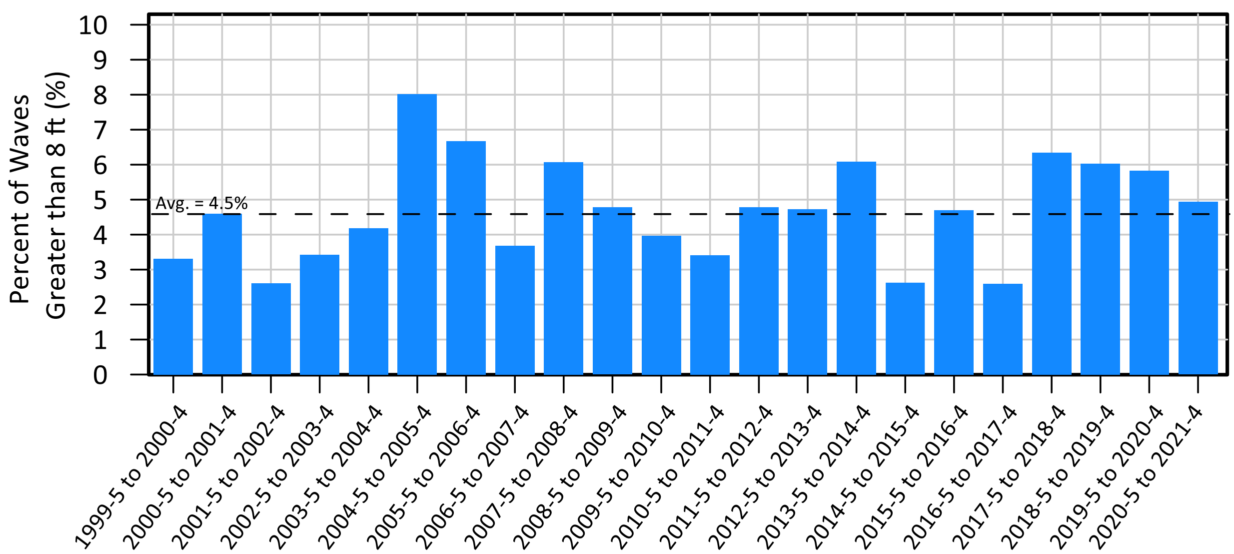

Figure 25: Percentage of waves greater than 8 ft during each monitoring year for WIS Station 63320.

An analysis of the wave energy from four directional bins was also performed. The wave energy was calculated using $E=1/8\ \rho g H^2$, where ρ is the water density (1,025 kg/m^3), g is the acceleration of gravity (m/s^2), and H is the significant wave height (m). The waves from the 37-yr wave record from 1980 to 2021 from Station 63320 were sorted by their respective directional bin, then the wave energy for each wave case was calculated with the energy equation. The energy for each bin was summed for each monitoring survey time period and then normalized based on the overall highest calculated annual energy in order to facilitate comparison. **Figure 26** presents the results of the wave energy analysis. The dashed lines represent the calculated and normalized annual energy values, and the 7-yr moving averages are depicted as solid lines.

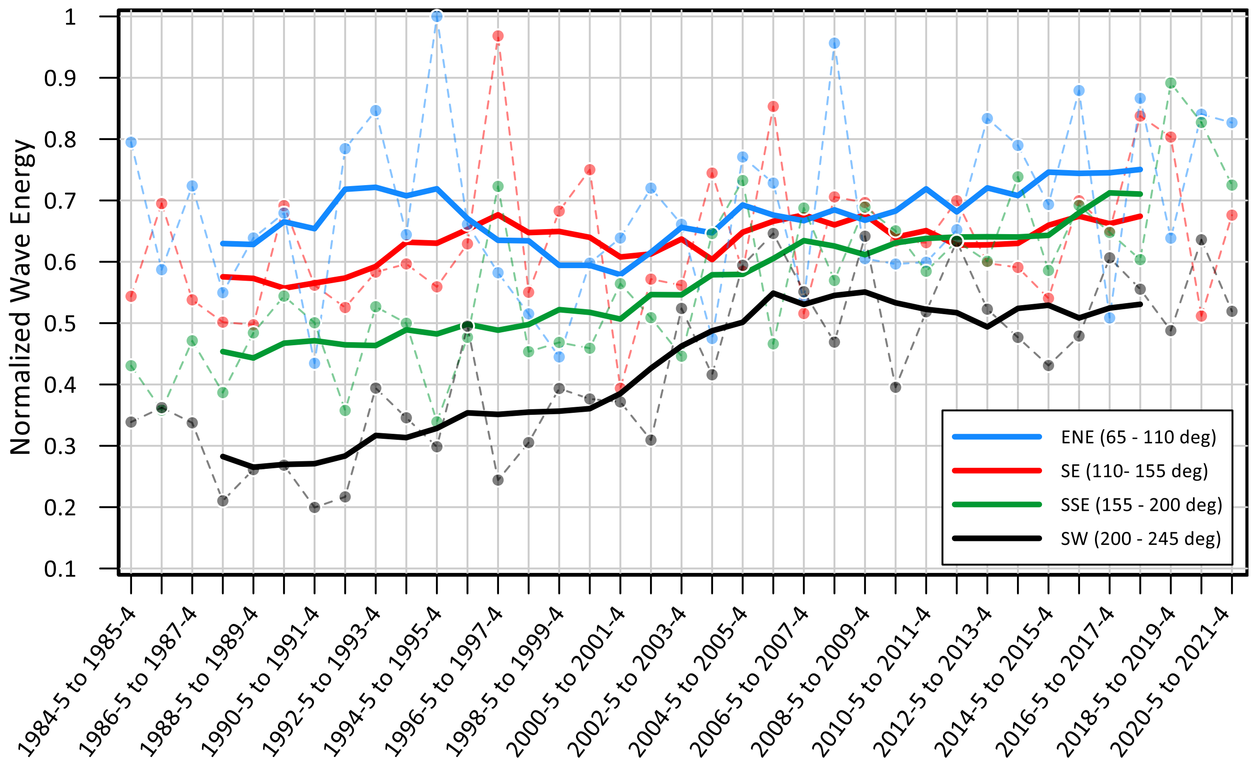

Figure 26: Yearly wave energy of four directional bins for WIS Station 63320 from 1984 to 2021. Dashed lines represent the calculated and normalized wave energy for each monitoring year (May-to-May) for each directional bin. Solid lines represent the 7-yr moving averages.

In general, the energy from each direction tended to increase during the data record, but the greatest amount of wave energy typically came from the east-northeast direction (blue line). However, the greatest increase in wave energy over time was observed from waves coming from the southwest (black line) and south-southeast (green line). This increase was particularly noticeable during the period for which beach monitoring data were available (1999 to 2022). The energy from the southwest direction exhibited the most rapid increase in energy from around summer 1999 to summer 2006.

Overall, the results from the wave climate analyses in this section do not suggest a strong link to the erosional and accretional trends which have occurred along eastern South Beach during the past two decades. It may be possible to associate some of the erosion along eastern South Beach with the overall increase in energy of the wave climate during the past two decades; however, it is believed that major storms are more influential in driving significant coastal erosion processes near the Club.

3.5.2 Wave Model

This section presents the results of the wave modeling effort performed during this study. The Simulating WAves Nearshore (SWAN) model (Booij et al., 1999) was utilized to propagate waves from the offshore to the BHI shoreline. The aim of the modeling was to improve understanding of the nearshore wave environment along eastern South Beach and southern East Beach in the vicinity of the Club. Understanding the kinds of waves that can be experienced near the Club informs the potential causes of erosion there and the feasibility of various erosion mitigation strategies that the Club may undertake. Appendix F.2 provides greater detail into the model setup process as well as the modeling results.

From the previously described wave climate analysis, it was determined to run the average wave conditions and storm conditions from four different directions: the northeast, southeast, south, and southwest. These average and storm wave conditions were calculated based on analysis of the wave data from WIS Station 63509. The nearshore bathymetry in the model was representative of October 2022 conditions and is presented in Appendix F.2. These conditions represent more recent, eroded conditions of the point and Club's shorefront. The annual beach profile survey data were used to represent the beach and nearshore, and the offshore bathymetry was downloaded from NOAA's Environmental Information webpage[3].

Figure 27 depicts the wave modeling results of the four average wave cases. The figures are zoomed to the nearshore region of the model to illustrate variations in wave behavior in the vicinity of the Club. The input significant wave height (Hs), wave period (Tp), wave direction (Dir.), wind speed (Wind), and wind direction (Wind Dir.) are listed on each figure. Wave height magnitudes are color-shaded, and wave directions are illustrated with arrows in the figure.

As the input average wave heights and periods were similar in each model simulation, the wave direction had the greatest influence on the wave field results presented in the figure. The southwest and south wave simulations (upper left and right plots, respectively) resulted in elevated wave heights in the vicinity of the Club, while the southeast and northeast waves (bottom left and right plots, respectively) result in minimal wave heights near the Club due to wave dissipation across Frying Pan Shoals. In all of the simulations, the wave heights just offshore of the Club were less than approximately 2.5 ft. Based on the model results and as can be intuited by the regional bathymetry of BHI, waves from the southwest direction have the greatest potential to exact morphological change along South Beach and the Shoals Club shorefront. Frying Pan Shoals provides a sheltering effect from waves with angles between southeast and northeast, resulting in minimal wave heights.

[3] https://www.ncei.noaa.gov/maps/grid-extract/

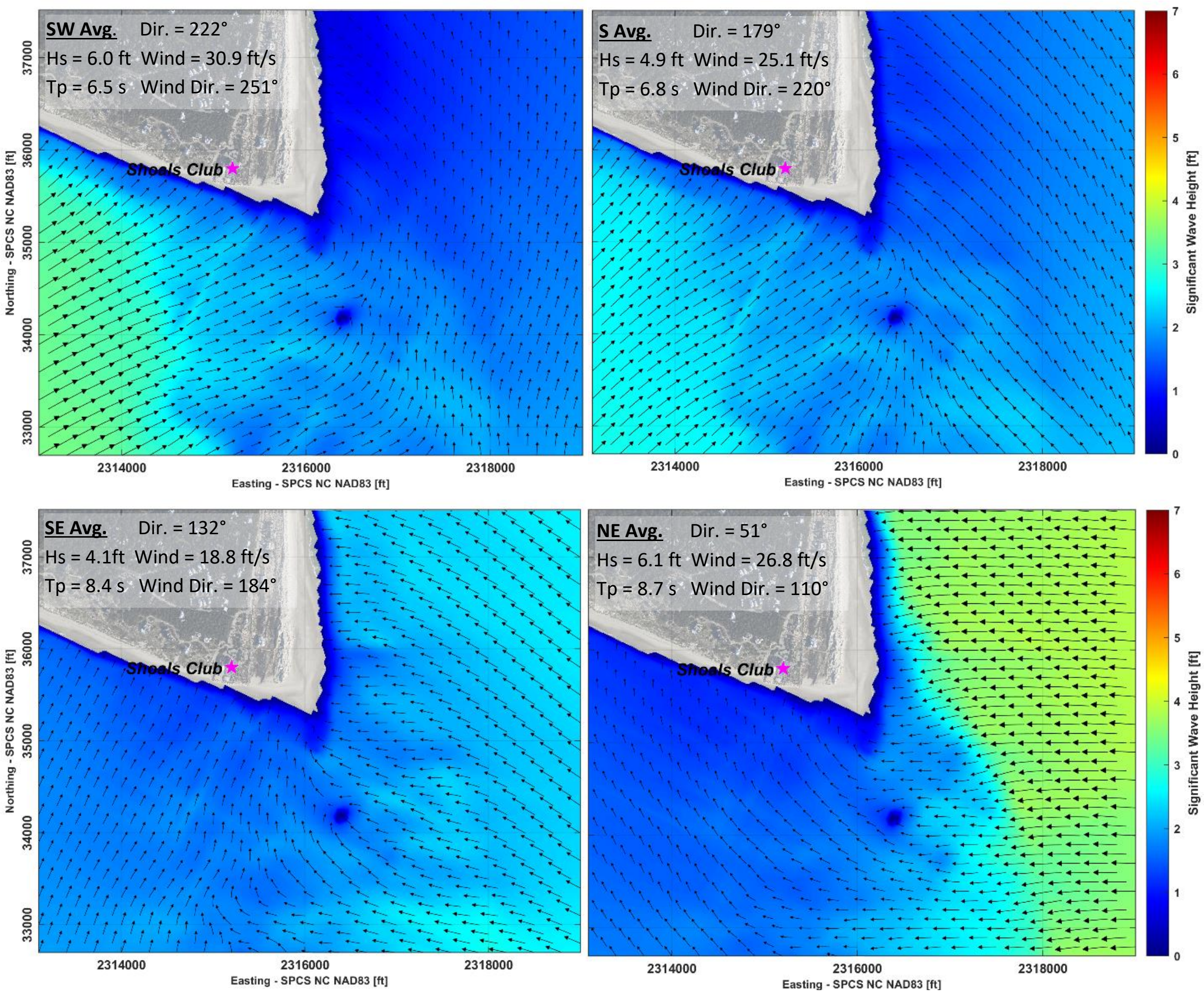

Figure 27: Wave modeling results of the four average wave cases on the October 2022 bathymetry. The input wave parameters are listed on each panel in the upper left corner.

In the southwest and south wave simulations, there was a discernable decrease in wave heights along South Beach with increasing proximity to the Cape Fear point. This alongshore decrease in wave heights is likely to result in an alongshore hydraulic gradient that induces the observed nearshore currents from west to east (Benedet and List, 2008). This current is likely only magnified by the wave refraction processes that redirect wave energy towards the point and Frying Pan Shoals, as can be observed in the figure. It is believed that the nearshore current along South Beach is the primary cause of erosion along eastern South Beach. Inspection of the southeast and northeast wave cases (bottom left and right, respectively, in the figure) suggests a similar hydraulic gradient exists on East Beach. Both the South Beach and East Beach alongshore currents are highly influential in reorienting the tip of the Cape Fear point.

Figure 28 depicts the wave modeling results of the four storm wave cases. The upper left graphic represents the peak of Hurricane Dorian in September 2019, with offshore wave heights of 32.6 ft, a period of 12.1 s, and a southwest wave direction. The upper right graphic represents Hurricane Floyd in September 1999, with offshore wave heights of 38.2 ft, a period of 14.7 s, and a southerly wave direction. The bottom left graphic represents Hurricane Maria in September 2017, with wave heights of 15.8 ft, a period of 9.1 s, and an east-southeast direction. Lastly, the lower right graphic represents a winter cold front in November 2021, with wave heights of 17.6 ft, a period of 11 s, and a northeast wave direction.

Similar to the average wave case simulations, the model results from the storm wave simulations indicated that the wave direction was the most influential parameter which affected wave heights in the vicinity of the Club. South and southwest wave directions result in larger wave heights along South Beach and the Club's shorefront, while northeast and southeast waves are mostly dissipated across the broad and shallow Frying Pan Shoals. However, despite the elevated offshore wave heights, the model results indicate that the majority of wave energy was dissipated offshore of the Club, far from the shoreline. The model results indicate that wave heights less than about 2 ft reach the shoreline in front of the Club, which are smaller waves than those simulated in the average wave cases. It is noted however that the storm wave simulations do not include the effects of storm surge; therefore, the waves experienced at the shoreline during each storm were likely larger.

Similar to the average wave simulations, an alongshore gradient in wave height is visible on South and East Beach, depending on the input wave direction, with wave heights decreasing with increasing proximity to Frying Pan Shoals. This gradient is even larger in the storm wave simulations, which would result in even larger alongshore hydraulic gradients, which in turn drive stronger point-directed, alongshore currents. It is believed that these currents are responsible for the majority of the beach erosion issues that the Club has experienced during the past decade and a half.

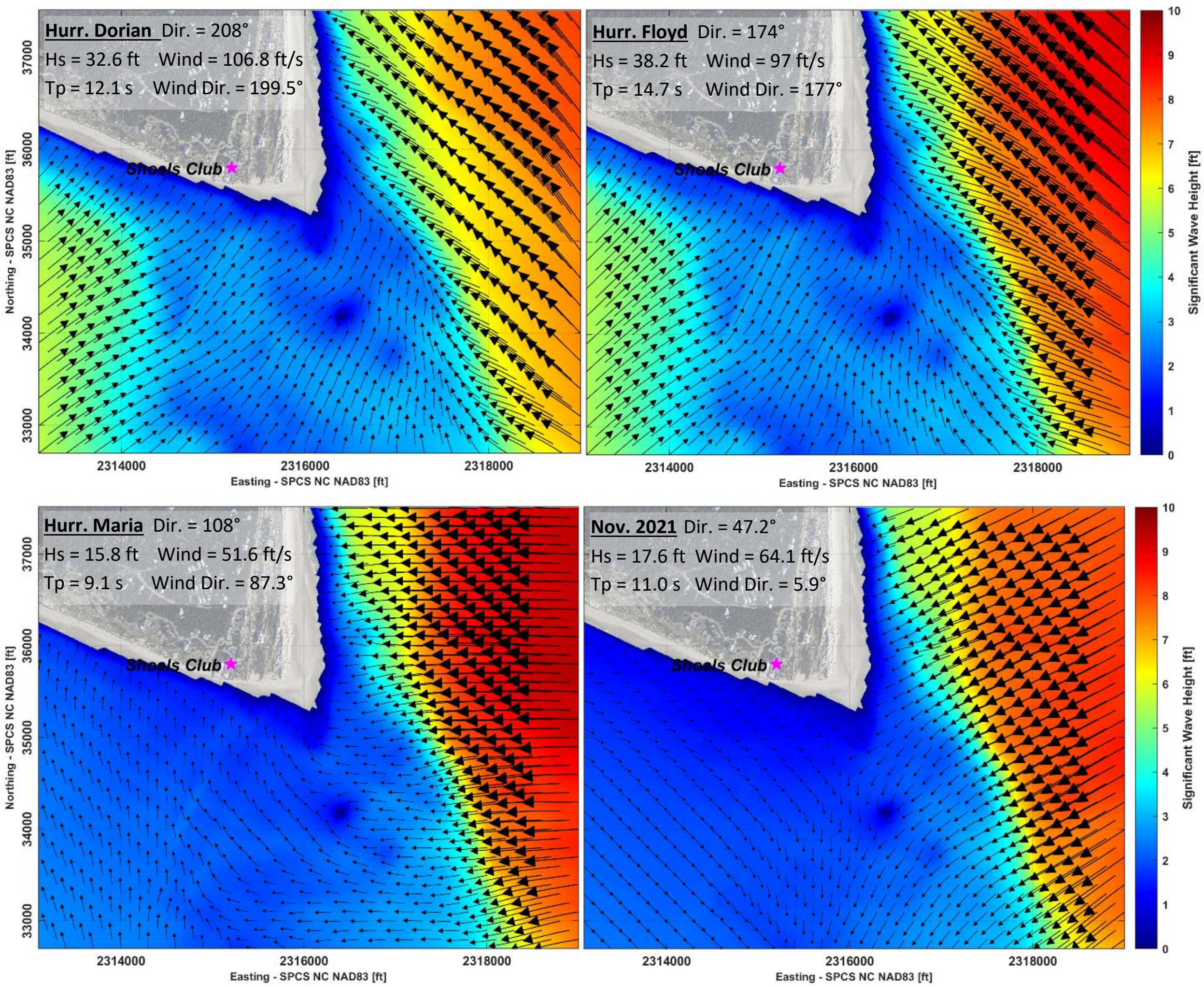

Figure 28: Wave modeling results of the four storm wave cases on the October 2022 bathymetry. The input wave parameters are listed on each panel in the upper left corner.

4. DISCUSSION - SEDIMENT TRANSPORT MECHANISMS

This section synthesizes the analyses conducted in this study and presents the findings related to sediment transport mechanisms and trends experienced along the Club's shorefront. As previously described, historical aerials were reviewed, a site visit was conducted, beach profile shoreline position and volume changes were calculated, variations in the wave climate during the past two decades were investigated, and a wave model was developed that simulated various characteristic wave conditions experienced in the vicinity of the Club.

At the broadest scale, littoral material located along East Beach is transported from north to south towards the Cape Fear point. Material located along South Beach east of approximately B-29 (in the vicinity of Starrush Trail) is transported from west to east towards the point. While these net transport directions are thought to be the predominant direction, brief periods of transport reversals can occur under certain wave conditions. Sand that moves from the north and west, to the point, is transported offshore into Frying Pan Shoals by wave action or alongshore, wave-driven currents. Based on the review of the historical aerials, beach profile volume changes, and MHW shoreline position changes, no evidence was found to suggest that sediment from Frying Pan Shoals has ever been transported back to the beach or foreshore region of Cape Fear in a great enough quantity to result in net positive volumetric changes to the beach. Within Frying Pan Shoals, sand is constantly being reworked and redistributed by the continuous forces of waves and currents.

Inspection of historic aerial photos revealed multiple and ephemeral east-west oriented, cross-shoal channels flowing through Frying Pan Shoals. The channels are thought to be formed by the alongshore gradient in wave heights along South and East Beach as well as locally generated, wind-driven waves. These channels migrate landward and seaward over time through the shoals. These channels act as a conduit for substantial quantities of sand, which is evidenced by the submerged "overwash" fans that are visible in numerous aerial photos (e.g., see **Figure 9**). Aerial photos from the most recent ten years illustrate a prominent alongshore channel immediately offshore of the shoreline in front of the Club. The migration of the channel is believed to be the principal cause of erosion along eastern South Beach. Similar erosion mechanisms can be observed along the shorelines adjacent to non-stabilized inlets along the North Carolina coastline. During the site visit conducted by CPE in July 2023, an alongshore current was observed flowing intensely to the east. The drone photography included in **Appendix H** illustrates the location of the cross-shoal channel.

Review of the historic aerials compiled from 2002 to 2022 was critical in understanding the evolution of the Cape Fear point. As previously described, the extents and orientation of the point has a significant impact on the surrounding beaches, including in front of the Club. The aerials revealed the growth of the point from October 2002 to around May 2007, during which time the point was oriented more to the south. The more southerly-oriented point configuration acted like a barrier to easterly-directed sediment transport along South Beach, trapping sand and contributing to the southerly growth of the feature and the widening of the beach fronting the Club. Sand traveling to the south along East Beach was then transported to the southern terminus of the point, further increasing its southerly extent. After May 2007, the point was oriented more to the east or southeast and gradually retreated to the north. The more easterly-directed point configuration then acted like a barrier to southerly-directed littoral material along East Beach, which contributed to the growth of East Beach. This configuration permitted sand traveling to the east along South Beach to be transported to the eastern terminus of the point, extending the point further east.

These observations lead to the question of why the point remained oriented to the south from at least 2002 to 2007, and why was it oriented more to the east after 2007. As discussed in **Section 3.1**, Hurricane Floyd made landfall near BHI in September 1999 and Hurricanes Dennis and Irene impacted the area during the same season. These storms closed New Inlet to the north, caused significant overwash along East Beach, and reoriented the Cape Fear point to the southwest. These changes indicate the substantial westward transport of sand across East Beach. Assuming Frying Pan Shoals also experienced significant westward transport of sand during these storm events, the cross-shoal channels located just offshore of the Club may have become clogged. The clogging of the channels may have been the mechanism that allowed for the southerly progradation of the point for the next eight years until its recession began sometime around early 2007. Additionally, review of the wave record following these hurricanes indicated relatively mild wave conditions for the next several years, which may explain why the orientation of the point remained to the south. Hurricanes Isabel (2003) and Ophellia (2005) passed far offshore to the east of the island during this time period, which may have also promoted the southerly orientation of the point. In September 2006 however, Tropical Storm Ernesto made landfall on Oak Island to the west of the Club, and this track likely caused intense, easterly-directed alongshore currents which potentially developed a cross-shoal channel that led to the point's gradual erosion thereafter. **Appendix B** includes an aerial image from October 2006, which illustrates the straightening of the coastline along eastern South Beach and southern East Beach.

Inspection of the aerial imagery in **Appendix B** and Google Earth Engine Timelapse indicate that the point was more directed to the east prior to Hurricane Floyd in 1999 and then returned to the east around eight years later. The point has remained easterly oriented until the latest aerial in October 2022. This observation simplistically suggests that the typical configuration of the point has been directed to the east. The historical shorelines in **Figure 6** and **Figure 13** depict the configuration of the Cape Fear point between 1945 and October 2022. In the figures it appears that the point has been oriented to the east/east-southeast more often than to the south, supporting the previous observation. Additionally, the various aerials and historical shorelines suggest that southerly orientation of the point has historically been more ephemeral in nature, which is consistent with the relatively short-term period of southerly orientation from around 1999 to 2007. Furthermore, **Figure 13** illustrates a gradual recession of the shoreline from its 1855 position to October 2022, with brief periods of shoreline advancement. It is possible that the eastern South Beach shoreline is undergoing a long-term, decadal-to-centennial scale, shoreline recession trend that only recently has begun to threaten the Club's infrastructure.

The MHW shoreline position change analysis presented in **Section 3.3** quantified the rate of shoreline advance along the Shoals Club shorefront from 1999 to 2006 and the subsequent retreat thereafter. Comparison of the evolution of the Cape Fear point with these shoreline position changes indicates a time lag between southerly advancement of the point shoreline with advancement in front of the Club, on the order of two to three years. This observation supports the idea that the point acts like a sediment barrier depending on its orientation. Once the southerly orientation of the point was well established in 2002, accretion occurred in front of the Club such that approximately 400 ft of advancement was measured between summer 2005 and 2006. This process is likely the primary mechanism by which accretion has episodically occurred along eastern South Beach. In contrast, once the point reached an easterly orientation around 2007 and proceeded to retreat to the north, the Club's shorefront began to gradually retreat over time.

The volume change analysis in Section 3.4 revealed an inverse trend of sand accretion and erosion along eastern South Beach and southern East Beach. While eastern South Beach accreted from at least 2002 to 2007, southern East Beach eroded. Conversely, as eastern South Beach experienced substantial erosion from 2007 to 2022, East Beach was experiencing a gradual increase in sand volume. The 6,000 ft of coastline from EB-1 to EB-7 gained an average of 4.2 cy/ft/yr above the depth of closure from 2011 to 2022, while the 6,000 ft of coastline from B-40 to B-55 lost an average of -9.1 cy/ft/yr during the same time period. Again, this observation supports the idea of the point acting as a barrier to alongshore sediment transport depending on its orientation.

In many coastal locations, a variation in sediment supply can result in temporary accretion or erosion of the beach. Along South Beach, sediment supply was not likely an issue given that the Village had placed approximately 10.2 million cy of sand since 1991. Roughly 4.9 million cy were placed east of the assumed sediment transport nodal point presented by Olsen (1989), providing an average annual supply of around 150,000 cy/yr to eastern South Beach. Despite this sand placement however, a recurring and appreciable accretion signal along the dry beach in the vicinity of the Club was not measured in the beach profile monitoring data following the renourishment events. Along East Beach, the 6,000 ft of shoreline from EB-1 to EB-7 accreted between around 10,000 and 40,000 cy/yr during different time periods from 2011 to 2022, indicating sediment transport was occurring from the north. The accreted sand was mostly stored on the southern half of the monitored beach and episodically transported from the point to the shoals during large wave events.

The analysis in Section 3.5.1 discussed the wave climate during the past two decades offshore of Bald Head Island. The analysis indicated that waves most frequently originated from the southeast, but a seasonal variation between the summer and winter wave climate was evident. Summer conditions exhibited smaller wave heights typically from the southeast, while winter conditions exhibited larger waves from all directions, but more commonly from the northeast. The average and modal wave conditions remained more or less constant during this time period. Maximum offshore wave heights varied from year to year but exceeded 12 ft in height every year.

The investigation of the variation in wave energy over time revealed an overall increase in energy from each wave direction. The largest increases in energy were experienced from waves originating from the southwest and south-southeast, waves which the modeling analysis revealed are most impactful to eastern South Beach. It is possible to associate some of the erosion along eastern South Beach with the overall increase in energy of the wave climate during the past decade and a half; however, it is believed that major storms are more influential in driving significant coastal erosion processes near the Club.

The wave modeling analysis in **Section 3.5.2** provided a better understanding of the influence that wave direction has on the wave heights experienced along both East Beach and South Beach. Waves originating from the southwest are most likely to have the greatest heights in front of the Club, and waves from between the northeast and southeast directions are mostly dissipated by Frying Pan Shoals before reaching the Club's shorefront. The modeling also indicated that even during some of the most intense offshore conditions, the wave heights along the Club's shorefront were less than 2 to 2.5 ft. Due to the location of the Club with respect to Frying Pan Shoals, the Club's shorefront appears to be largely sheltered from offshore waves. However, as waves approach and refract around Frying Pan Shoals, considerable variations in wave height along both South and East Beaches develop. This alongshore variation may induce a hydraulic gradient along both South and East Beaches that drives alongshore currents towards the shoals. The alongshore (cross-shoal) current adjacent to eastern South Beach is believed to be the primary driver of erosion along the Club's shorefront for at least the past decade.

5. EROSION MITIGATION ALTERNATIVES

Based on the analyses described in **Section 3** and the conclusions drawn in **Section 4,** six conceptual alternatives have been developed with the intent of mitigating future erosion impacts to the Club. The proposed alternatives focused on slowing the local erosion rate, periodically adding sand into the system, and/or otherwise managing the oceanfront portion of the Club to ensure long-term future use. Note that the concept figures presented in the following paragraphs are included for concept visualization purposes only. Extensive design analyses would be required before implementing any of the proposed alternatives.

Erosion mitigation strategies are generally described by two categories: hard and soft engineering. Soft engineering alternatives represent strategies that mimic natural processes in order to provide protection from potentially adverse impacts from the ocean. In an open ocean environment like the Shoals Club, the typical soft engineering strategy involves beach renourishment, like what has occurred along western South Beach for decades. Hard engineering alternatives involve the construction of strategically placed structures that either slow erosion by decreasing the sediment transport rates and holding sand in a desired location (groins or breakwaters), or by armoring a shoreline and maintaining a position in an attempt to halt future erosion of a shoreline (seawalls and bulkheads). Unlike soft engineering strategies, which attempt to mimic natural processes, hard engineering strategies attempt to modify natural processes.

The following descriptions of alternatives include an opinion of probable cost, which includes engineering design, environmental permitting, sediment compatibility analyses, construction bidding document development, bidding assistance, and construction-related costs. These opinions of probable cost are preliminary and would need to be reevaluated after more detailed engineering design.

5.1 Alternative 1 - Periodic Beach Renourishment

This strategy involves the mechanical or hydraulic placement of beach-compatible sand across the wet and dry portions of beach along the Club's shorefront through collaboration with the federal government or the Village's recurring beach renourishment projects. As previously stated, beach nourishment projects are constructed every 2 to 3 years along South Beach through projects sponsored by the federal government or the Village. The federal projects involve dredging portions of the Cape Fear River navigation channel, and the Village's projects involve the dredging of sand from offshore borrow areas. Both projects place fill along various portions of South Beach and West Beach. Historically, the eastern limit of fill of these projects has been significantly west of the Shoals Club.

The intent of this alternative would be to extend the placement area of both the federal and Village's projects further east to include the Club's shorefront. As part of this project, a sufficient quantity of sand should be placed to mitigate for expected erosion rates. Typically, the initial construction of a beach nourishment project includes the construction of a "design beach" and the placement of "advanced fill." The design beach is constructed so as to provide a designed level of protection (e.g., 5-, 10-, or 50-year storm), and the advanced fill is additional sand placed seaward of the design beach that is meant to protect the design beach until the next renourishment event.

Through recent discussions with the Village, CPE has learned that beach fill along the east end of South Beach has been integrated into the Village's proposed 2024/2025 beach nourishment project. A design has already been developed for this project and permit applications have been submitted. The proposed layout of the beach fill project is illustrated in Figure 29. The design calls for the placement of 500,000 cy along 6,000 ft of beach, or an average fill density of 83 cy/ft. The largest placement area in the figure is along the eastern end of South Beach. It is assumed that this area may receive on the order of 100 cy/ft of fill.

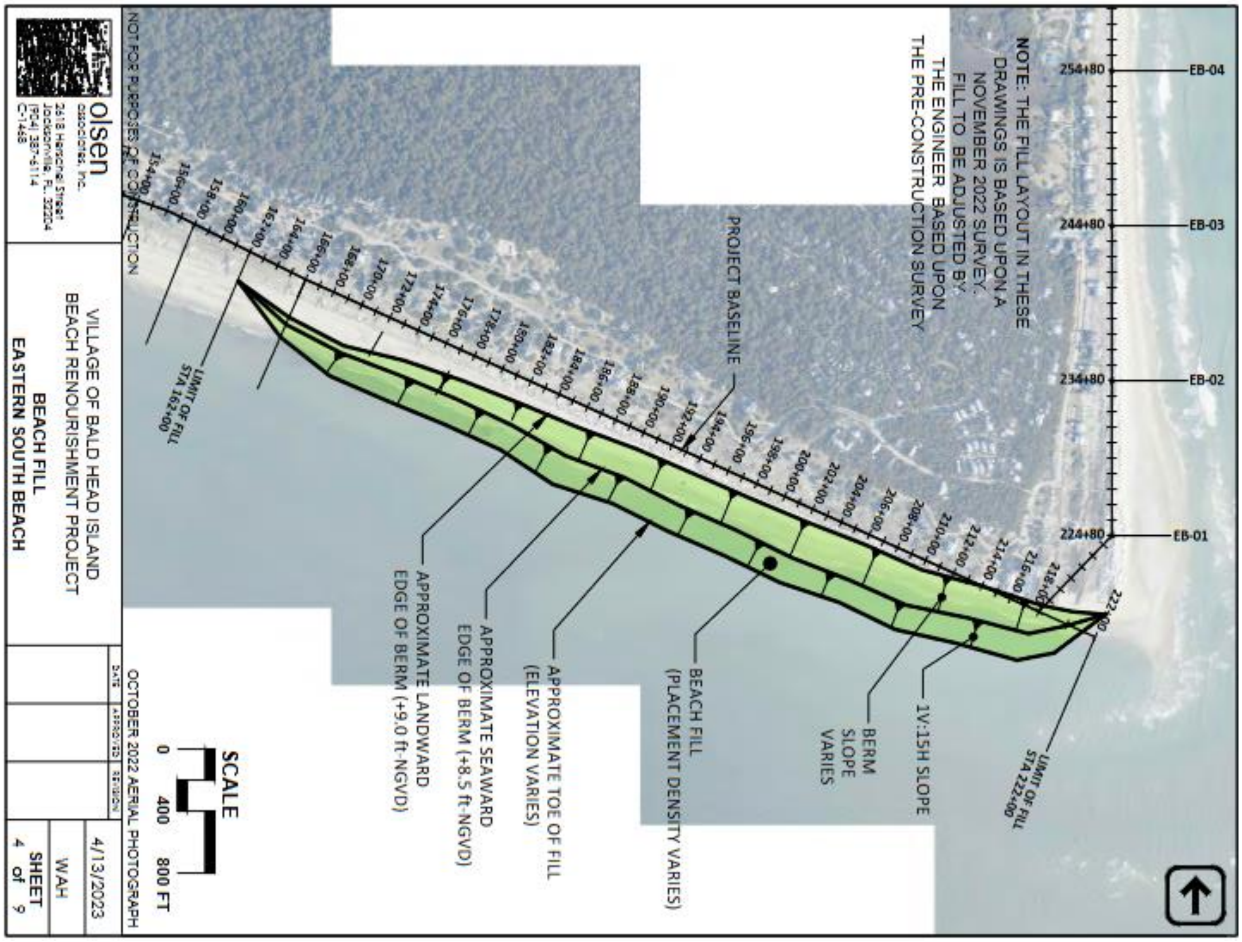

Figure 29: Permit sketch for beach fill placement along the east end of South Beach.

The initial, conceptual-level alternative aims to recreate the 2,000 ft segment of beach from B-50 to B-55 to a condition similar to what existed in May 2018. At that time the beach had a robust dune system and moderately wide beach. To recreate those conditions would require approximately 122,000 cy of fill. This volume would be considered the “design beach” volume.

In Section 3.4, the erosion rate from 2015 to 2022 along the 2,000 ft of beach from B-50 to B-55 was calculated at approximately -70,000 cy/yr. Using this rate as an initial estimate for expected future erosion and assuming a project interval of every three years, a single project could involve the placement of 210,000 cy. This fill volume is considered the “advanced fill” volume.

Combination of the design and advanced beach fill volumes equates to approximately 332,000 cy, or 166 cy/ft, for the initial construction of the design alternative. If the Village's proposed project in 2025 places around 100 cy/ft along the proposed 2,000 ft of beach considered under Alternative 1, the construction of the full recommended beach fill would require an additional 132,000 cy (66 cy/ft) of fill. Therefore, in order to place the recommended fill density from B-50 to B-55, an additional 132,000 cy of fill would be required. Assuming the Club would only contribute to the placement of this volume of sand (i.e., pre-construction engineering, mobilization costs, etc. would be borne by the Village), the opinion of probable cost is $1.5M.

Currently, the Village/federal renourishment projects dredge material located within the federal channel or various offshore borrow areas. As a future consideration for the Club, a permit application for an additional borrow area within Frying Pan Shoals (see **Figure 5**) has been under review for the Village's projects since 2017. Assuming this permit is authorized in the future, the location of this borrow area may be advantageous for the Club given the shorter distance from the borrow site to the project area. This assumes that dredging of the proposed borrow area would not negatively impact the Club shorefront by redirecting wave energy towards the Club (not investigated in this study). However, at the time of publishing this report, the issuance of a permit for the use of the Frying Pan Shoals borrow area has not occurred, as the process has been stalled in the request for additional information stage with the National Marine Fisheries Service (Olsen, 2022a).

5.2 Alternative 2 - Re-Alignment of Cross-Shoal Channel and Beach Nourishment

As described in **Section 4**, the alongshore currents that cut through Frying Pan Shoals near the Cape Fear point are considered the primary drivers of erosion along eastern South Beach. Observations suggest that the closer to shore the channels are situated, the higher the rate of erosion. When the channel is located further offshore, the erosional stress the currents exerts on the beach may decrease and, in turn, reduces the rate of erosion. The objective of this concept is to create a dominant cross-shoal channel sufficiently seaward of the point through the use of a hydraulic dredge. By repositioning the channel further seaward, the channels located more proximate to the shoreline of the Club may infill and reduce sediment transport directly off of the upper portion of the beach. The material dredged to create the channel would be placed along the beach seaward of the Club. The beach nourishment project would be similar in size and layout as that described in Alternative 1: approximately 330,000 cy from B-50 to B-55. The dredge channel configuration would need to be designed to accommodate an ocean-going dredge. To that end, the channel would need a minimum depth of around -14 ft MLLW, a width of 300 ft, and 3,000 to 4,000 ft long to cut across the entire shoal. **Figure 30** illustrates this concept. The orange lines represent the cross-shore channels observed during the July 2023 site visit. The landwardmost channel was located immediately offshore of the beach, and a shore-parallel current was observed flowing through the channel. The yellow dashed line represents the hypothetical channel borrow area from which material would be dredged and placed into the red dashed area. The opinion of probable cost for this project is $5.2M.

This concept will need to be vetted through the use of advanced numerical modeling. Such modeling could be developed to evaluate the potential consequences of dredging the nearshore channel including channel infilling rates, altered wave refraction patterns, the resulting beach erosion/accretion patterns, and altered currents. Additionally, permitting this type of alternative would likely be challenging based on the Village's attempt to permit the dredging of sand from other portions of Frying Pan Shoals.

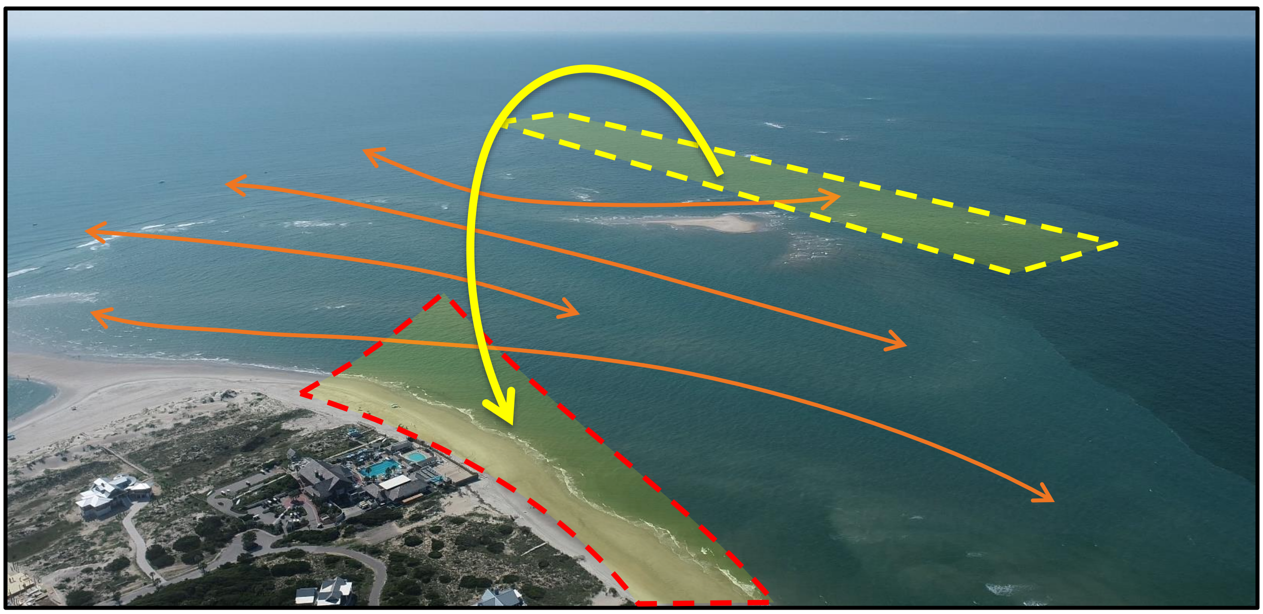

Figure 30: Location of the cross-shoal channels (orange lines) flowing through Frying Pan Shoals in July 2023. The yellow dashed line illustrates the concept of a dredged channel through the Shoals, and the red dashed line represents the Alternative 1 placement layout.

5.3 Alternative 3 - Cape Fear Point Sand Transfer

This concept involves the periodic mechanical transfer of sand from the Cape Fear point to the oceanfront along the Club's property. The location from where sand would be transferred would be dependent on the configuration of the point at any given time. **Figure 31** presents an example of this concept based on conditions in April 2019. The area labeled as the borrow area is a rectangle measuring approximately 500 ft by 800 ft. If three feet of sand were excavated from the top of this area, approximately 40,000 cy of sand would be available for placement along the area indicated in the figure. Given the reduced placement volume, the alongshore extents of the placement area have been reduced to the 500 ft of the Club and adjacent shoreline, resulting in a fill density of approximately 120 cy/ft. The borrow area dimensions, excavation depth, and resulting excavation volume would vary depending on the conditions of the point at the time of construction. As previously established, the point's orientation is highly variable, suggesting that this concept would be opportunistic in nature. That is, whenever the point reaches an appropriate configuration to justify the excavation of its sand, the Club could take advantage of the opportunity to bolster its shorefront.

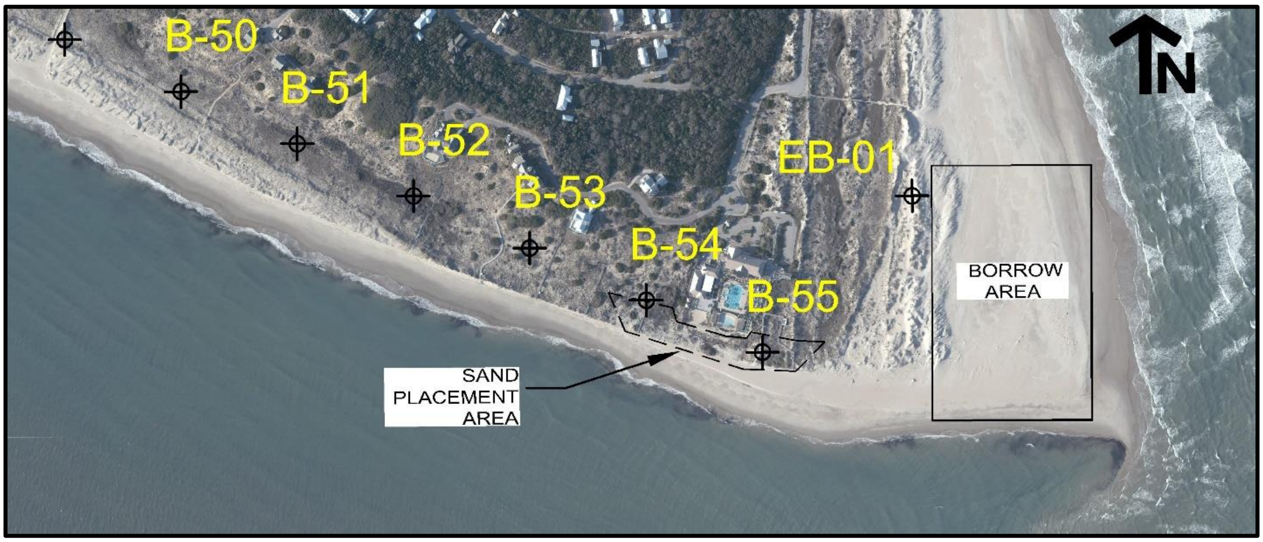

Figure 31: Example sand borrow area located on the Cape Fear point. Aerial imagery from April 2019.

The overall logistics to construct this conceptual project are relatively straight forward. The sand transfer could be accomplished with the use of excavators, offroad dump trucks, and bulldozers to handle the sand and reshape the beach. The cost for construction would be lower than that required to mobilize a hydraulic dredge. However, as a similar project has not been permitted in the area, the challenges related to securing state and federal permits for a project of this kind are unknown. Reasonable assurance would need to be provided that negative impacts would not occur to the upland properties fronting the borrow area along East Beach. Based on a cursory review of the example borrow area in **Figure 31** and an excavation depth of 3 ft, the borrow area may refill within one to two years. The opinion of probable cost for this project is $1.3M.

5.4 Alternative 4 - Geotube Groin Field

This concept involves the strategic placement of sand-filled geotubes along the eastern end of South Beach. Similar to Alternative 2 and 4, the objective of the groin field would be to decrease the erosion rate in this area to a lower, more manageable rate. **Figure 32** presents an example layout of the geotube groin field concept. In the figure, multiple groins have been placed west of the Club in order to decrease the erosion rate in that area. Ideally, the initial construction of the project would coincide with a beach renourishment project. Further evaluation is required to estimate the frequency at which additional sand would need to be added to the area after initial construction of the groin field and placement of sand.

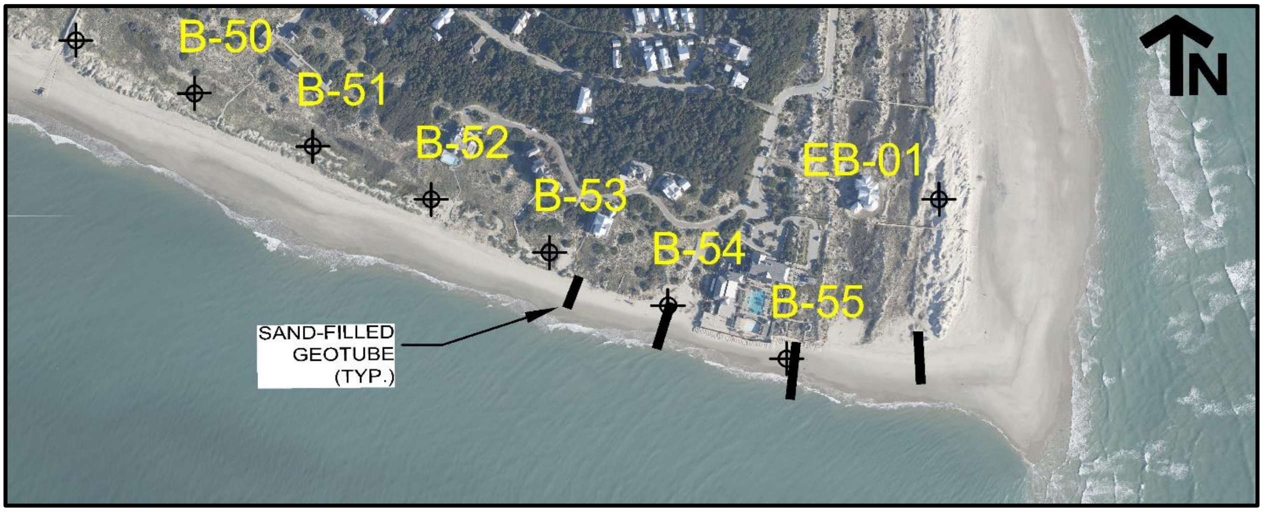

Figure 32: Example layout of sand-filled, geotube groin field along eastern South Beach. Aerial imagery from October 2022.

As a similar project was permitted and constructed along western South Beach back in the 1990s, which has historically performed as expected, and given the unique geomorphological setting of the project area, it is assumed that this proposed concept is permittable. However, in 2003 the North Carolina state legislature banned the construction of new, permanent erosion control structures along the North Carolina coast. Further investigation into the feasibility of this alternative, from a permitting perspective, is needed.

Initial construction costs would be less than a permanent rock or concrete structure, but typically maintenance of geotube structures is required more frequently than rock or concrete structures. A groin field design study would need to be conducted in order to optimize the placement and dimensions of the individual groins.

In order to provide a cost comparison for this conceptual-level alternative, this report assumes placement of 600 ft of sand filled geotube. Based on the cost to replace ten of the Village's geotube groins in 2019, the opinion of probable cost for this alternative is $1.1M. This cost does not include periodic maintenance of the geotubes or the concurrent placement of beach fill (assumed to be placed by the Village or USACE).

5.5 Alternative 5 - Terminal Groin

This concept involves the construction of a terminal groin located south and east of the Shoals Club. Again, the goal of the structure is to capture easterly transported sand and slow the rate at which sand is transported from the Cape Fear point to Frying Pan Shoals. A terminal groin was constructed on the western end of South Beach in 2015 to combat the chronic erosion problems the area experienced and has generally performed as intended. **Figure 33** illustrates an example layout of a terminal groin intended to capture sand along South Beach. The landward 200 ft of the groin is oriented to the northeast to prevent flanking from East Beach in the case of excessive erosion. The overall length of the groin in the figure is 675 ft. Depending on continued monitoring of East Beach, it may be necessary to construct an additional, easterly oriented groin spur to capture southerly transported sand along southern East Beach. The spur would prevent excessive erosion from occurring along southern East Beach.

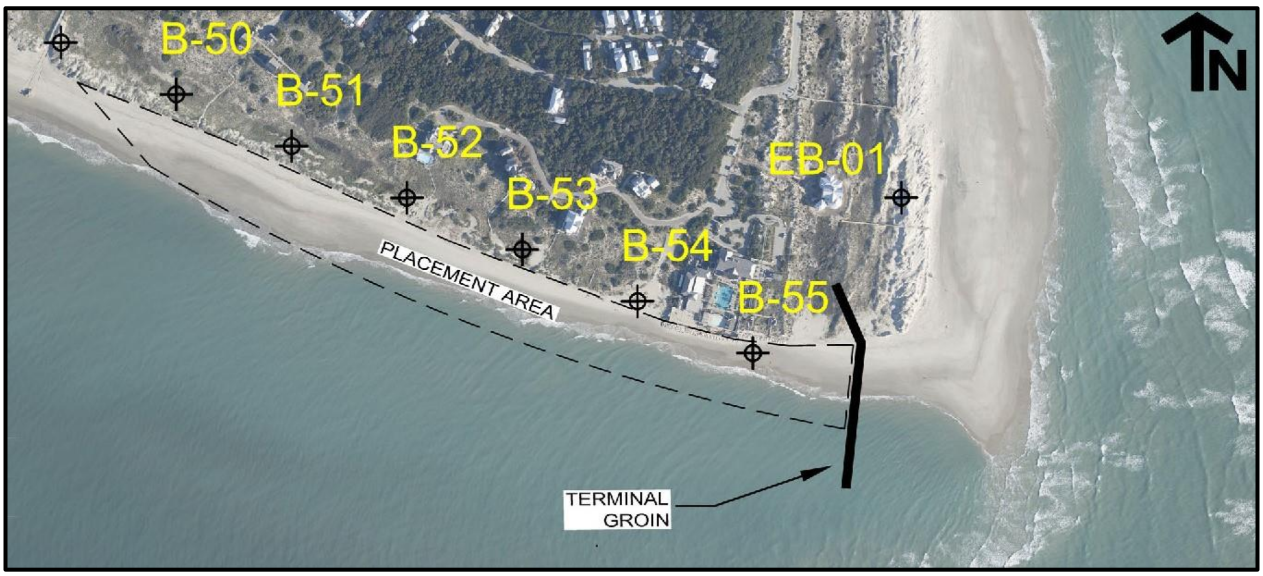

Figure 33: Example layout of a terminal groin at the point of Cape Fear. Aerial imagery from October 2022.

The groin would be constructed as a rubble mound structure with large stones. The structure would capture easterly transported sand along South Beach. The configuration of the groin (rock size, structure elevation and length, etc.) would require detailed design analysis that would likely include advanced numerical modeling. Beach renourishment projects are typically constructed immediately before or after a terminal groin is constructed in order to facilitate the groin's construction and/or provide the immediate shore protection to the upland. However, given that the Village is pursuing beach nourishment along the east end of South Beach, the cost for sand for this alternative has been assumed to be part of the Village's beach nourishment program. Even with this assumption, this concept would still be the most expensive erosion mitigation alternative considered in this report. The opinion of probable cost for the terminal groin is $7.4M.

Additionally, receiving state and federal authorization for the construction of a terminal groin would be challenging and not necessarily guaranteed. Special legislation may be required to allow this proposed groin to be permitted.

5.6 Alternative 6 - Managed Retreat

This concept involves the relocation of portions of the Club infrastructure to a more landward location, increasing its distance from the threat of wave attack. This strategy has been successfully employed at locations throughout the world in instances when combatting shoreline retreat was unfeasible and/or undesired. As mentioned in **Section 4**, eastern South Beach has been experiencing an overall trend of shoreline retreat since at least the mid-1800s, and no natural mechanism was identified through the course of this investigation to suggest a reversal or significant slowing of this trend is likely. If a programmatic strategy to combat this erosion trend with at least one or more of the above concepts is not initiated, it is possible that the shoreline will continue to retreat, further threatening the Club's facility.

Through recent conversations with the Club, CPE has learned that an adjacent property was recently purchased by the Club. The managed retreat strategy could be implemented through a phased approach, whereby infrastructure could be incrementally added to the newly purchased property over a 5-to-10-year time horizon. The existing Club property wouldn't need to be necessarily abandoned but could instead be reconfigured to adapt more easily to changing coastal conditions. Depending on the availability and cost of land for purchase, this option may be more economically feasible than any single dredging project alternative.

While a detailed analysis of real estate values and cost estimates for relocation and demolition of various Club facilities was beyond the scope of this study, an opinion of cost was generated for comparison purposes. The opinion of cost utilized a cost of $1.7M for the purchase of an adjacent property. A cost of approximately $400,000 has been assumed for the first phase of the managed retreat, which would likely involve the design, permitting, and construction associated with the relocation of the seawardmost pool and adjacent recreational facilities to the adjacent property. This cost also assumes demolition and removal of the existing facilities. The opinion of probable cost for the first phase of this alternative is $2.2M.

Based on the analysis presented in **Section 3.3**, the MHW shoreline at B-55 adjacent to the Club has steadily retreated at an average rate of -43 ft/yr during the past 14 years. The seawardmost pool and surrounding deck has a cross-shore width of around 70 ft. If (1) recent erosion rates continue for the foreseeable future and (2) the Village's proposed beach renourishment project in 2025 advances the MHW shoreline in front of the Club by around 100 ft, implementation of the first phase of this alternative may prevent damage to the Club's infrastructure for a period of approximately four years.

6. SUMMARY

This report documented the study of the causes of the long-term erosion and accretion that has occurred along the Shoals Club shorefront during the last two decades. Previous studies related to the morphological changes that have occurred in the area were reviewed and incorporated into this study where appropriate. Recent topographic and bathymetric survey data, LIDAR data, and historical aerials were used to evaluate shoreline and volume changes and understand sediment transport pathways. Likewise, topographic and bathymetric data as well as wave data were compiled to perform a wave modeling analysis. These analyses were synthesized to develop an understanding of the recent erosion trends. Based on the results of these analyses, six alternatives aimed at mitigating the recent erosional impacts were presented.

Review of the historic aerial imagery proximate to the Club revealed the link between the orientation of the Cape Fear point and width of the dry beach in front of the Club. When the point is oriented to the south, it acts as a barrier to easterly transported sand along South Beach. Transported sand is impounded on the point, resulting in updrift accretion and an increase in beach width. It is believed that this mechanism is the primary driver of accretion along the Club's shorefront. When the point is oriented to the east, southerly transported sand on East Beach is impounded on the point, which, in turn, results in accretion and an increase in beach width along southern East Beach. Analysis of the beach profile volume change and MHW shoreline position changes along South and East Beaches confirm these observations.

The wave modeling results indicated that a relatively small fraction of the offshore wave energy actually reaches the beach in front of the Club. This analysis also revealed an alongshore variation in wave heights along East and South Beach. That is, wave heights decrease with increasing proximity to the point. This variation in wave height induces an alongshore hydraulic gradient on both South and East Beaches, resulting in point-directed alongshore currents. These alongshore currents intersect at the tip of the Cape Fear point. When one current overpowers the other, the tip of the point reorients accordingly. Along South Beach, this alongshore (cross-shoal) current meanders through Frying Pan Shoals based on shoal locations and strength of currents. When the point is oriented to the south, it pushes the cross-shoal current further offshore and away from the Club's shorefront. When the point is oriented to the east, the current often meanders immediately offshore of the Club's beach and causes increased erosion rates along eastern South Beach. The cross-shoal current is reinforced by the local wave refraction patterns near the point, which directs waves toward Frying Pan Shoals. This meandering cross-shoal current is believed to be the primary driver of erosion along the Club's shorefront.

Powerful winter cold fronts and summer hurricanes are capable of reorienting the point in a short period of time. During the summer of 1999, Bald Head Island was impacted by three powerful hurricanes, including Hurricane Floyd in September, which made landfall near the Island. These hurricanes reoriented the point to a southwesterly orientation and caused a westward transport of nearshore sand across East Beach and Frying Pan Shoals. The westward transported sand potentially clogged the cross-shoal channels within Frying Pan Shoals, setting up ideal conditions for the southward advance of the point. The following years exhibited relatively calm wave conditions, maintaining the point in a southerly orientation. From 1999 to the summer of 2006, the point and the MHW shoreline in front of the Club steadily advanced to the south by hundreds of feet. In September 2006, Tropical Storm Ernesto made landfall on Oak Island to the west of Bald Head Island and likely caused powerful cross-shoal currents to reorient the point in a more easterly direction, allowing cross-shoal channels to meander closer to the point. From summer 2007 to May 2022, the point and the MHW shoreline in front of the Club steadily retreated hundreds of feet, which forced the Club to install a temporary sandbag revetment in June 2022.

Six alternatives aimed at mitigating the recent erosional impacts and slowing erosion rates along eastern South Beach were developed for the Club's consideration. Each alternative was developed to mitigate the erosion concerns with a different approach to in order to improve overall cost and/or ability to acquire state and federal permits. **Table 3** summarizes the implementation schedule as well as the approximate costs of each alternative. These estimates are for preliminary budget purposes only and are presented in 2023-dollar values. These estimates may be refined during value engineering and final design. CPE has no control over the timing, availability, cost of labor, equipment or materials, market conditions, or methods that may affect future pricing. Accordingly, no warranty can be provided that the actual bids or negotiated prices will not vary from these estimates.

Table 3: Summary of implementation schedule and approximate project cost.

Alternative	Strategy	Implementation Schedule (years)	Approximate Project Cost
1	Beach Renourishment	1-2	$1,450,000
2	Dredge Cross-Shoal Channel	3-4	$5,170,000
3	Point Sand Transfer	1-2	$1,300,000
4	Geotube Groin Field	3-5	$1,050,000
5	Terminal Groin	3-5	$7,410,000
6	Managed Retreat	1	$2,150,000

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