A Re-evaluation of Data and Sand Resource Need, Use, and Availability in Northeastern (Dare County) North Carolina

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Abstract

Hurricane Sandy had a significant impact on northeastern North Carolina, particularly along the Outer Banks north of Cape Hatteras in Dare County. As a result of strong winds, large waves and storm surge, significant erosion and infrastructure damage occurred in several locations. Today, the dune-beach system remains in a compromised condition in several areas of Dare County, and a few towns and the County are planning for beach nourishment. Since the NC Beach and Inlet Management Plan (BIMP) (2011), a number of studies have collected new data to evaluate sand resources in this region. A compilation, comparison and reassessment of data was conducted in this study to help inform work being planned and identify future needs. Data comparison shows that while offshore sand sources are present in State and federal waters, there are discrepancies in the sand thickness estimates and spatial patterns.

Introduction and Background

Sandy coastlines around the world are particularly dynamic, and data show that the majority of North Carolina's coast is eroding (NC Division of Coastal Management, 2012). The focus of this report is on the need for and availability of sand resources and related data in the northeastern portion of the State of North Carolina, specifically Dare County (Fig. 1). This region juts seaward into the Atlantic Ocean, making it subject to powerful waves and strong currents over a narrow shelf. Along this

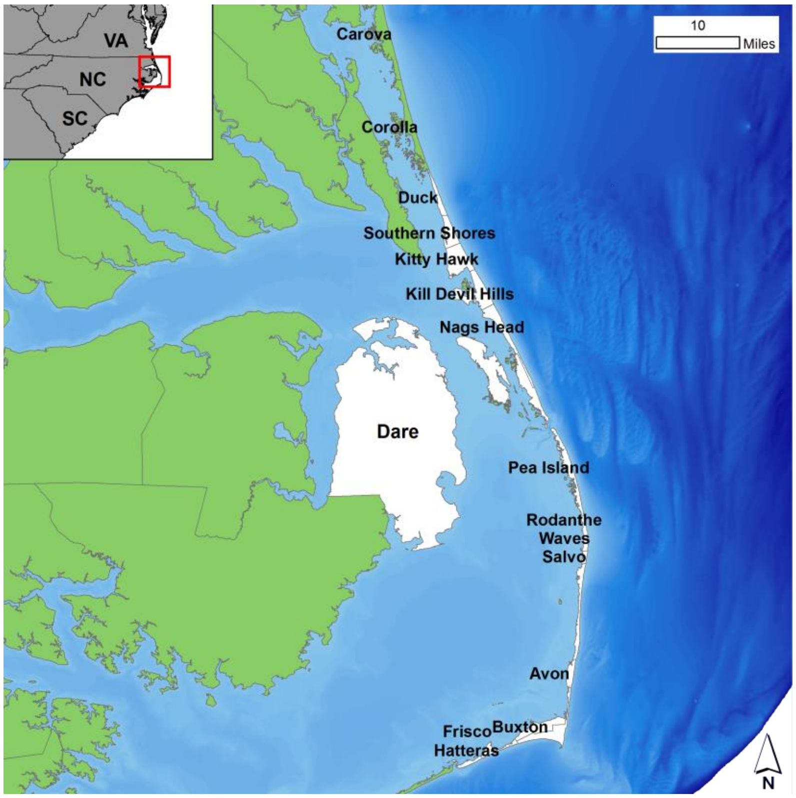

Fig. 1. Map of northeastern NC showing Dare County and its oceanside towns. Dare County includes a portion of mainland NC, Roanoke Island, and a long stretch of the Outer Banks barrier-island system, including towns from Duck to Hatteras.

coast, there are multiple areas that are challenging to manage as a result of long-term and recent coastal change (Fig. 2; Riggs et al., 2009).

Dare County extends from Duck (near the Virginia border) to Hatteras (Fig. 1). The adjacent vast sounds and pristine beaches, some of which belong to the Cape Hatteras National Seashore, are well-known for a plethora of activities such as surfing, fishing and boating. These outdoor recreational activities along with cultural landmarks including the Wright Brothers Memorial, Fort Raleigh National Park, and the Cape Hatteras Lighthouse combine to draw millions of tourists annually (Table 1). Dare County is a critical economic asset, being the third largest NC county in terms of tourism expenditures, having surpassed the $1 billion mark in 2014 (Economic Development Partnership of NC, 2016).

Much of Dare County's coastal appeal is related to its extensive sandy ocean beaches. But, as a result of its geologic construction, storm activity (i.e., frequent nor'easters and hurricanes), and ongoing sea-level rise, shoreline erosion is widespread (Fig. 2). Erosion and sand limitations are a product of the surrounding geology and the lack of modern fluvial sediment sources nearby. Shorelines have receded as wind and overwash have transported sediment across (landward), along and locally offshore of this coastline (Inman and Dolan, 1989; McNinch, 2004; Riggs et al., 2009). Unlithified sand deposits overlie the post-glacial transgressive ravinement surface in some areas. These Holocene or "modern" sands are variably thick on the continental shelf. The bathymetry of the region is characterized by a series of submarine ridges and shoals which are generally believed to reflect sedimentary deposition and reworking associated with the Holocene transgression (Fig. 1). High-relief shoal complexes, such as Platt, Wimble and Diamond shoals, contain particularly thick (>10 ft) and large volumes of Holocene sand (Thieler et al., 2013; 2014).

Table 1: Visitors to Dare County sites in 2014 from the Outer Banks Visitors Bureau.

Site	Number Visitors 2014
Aquarium	271,800
Bodie Island Lighthouse Climbers	39,340
Cape Hatteras National Seashore	2,266,579
Cape Hatteras Lighthouse Climbers	125,294
Cape Hatteras Visitor's Center	420,190
Fort Raleigh	266,219
Hatteras Ferry Passengers	654,566
Jennette's Pier	182,266
Jockey's Ridge	1,237,276
Total	**5,463,530**

The frequent nor'easters of the winter months and hurricane strikes during the summer and fall are key drivers of the erosion measured in Dare County (Fig. 2). While there has not been a direct strike from a strong Category 2 or greater storm since Hurricane Isabel in 2003, several influential storms have impacted the area recently. Although only a Category 1 storm, Hurricane Irene in 2011 crossed the expansive Albemarle-Pamlico estuarine system resulting in extensive sound-side flooding and a now-closed inlet (Mulligan et al., 2014). Hurricane Arthur in 2014 also was a sound-side flooding event, but impacts were more restricted for the relatively small, weak and fast-moving Category 2 storm. Despite passing ~150 km offshore, the Category 2 Hurricane Sandy in 2012 caused significant problems in Dare County. This massive system brought sustained winds of 49 knots (gusts to 60 knots) and wave heights of 20 ft (at the 55 ft "wvrdr630" buoy site) at the U.S. Army Corps of Engineers (USACE) Field Research Facility (FRF) in Duck, NC, a testimony to its far-reaching influence. A ~7 ft ocean water level (relative to MLLW) was experienced in Dare County (measured at the USACE FRF), and these high water levels coupled with the very large waves led to significant erosion, overwash and eventually dune losses that enabled flooding. The Virginia Dare Trail (i.e., the "Beach Road") was completely undermined in Kitty Hawk, and the Croatan Highway (U.S. Route 158), the main road along the Outer Banks, was deeply flooded, interrupting traffic along the island. Approximately $900,000 was spent by the State to repair a portion of roadway and fronting dune at one locality in Kitty Hawk where erosion was severe, and this stretch of roadway has had continued problems since.

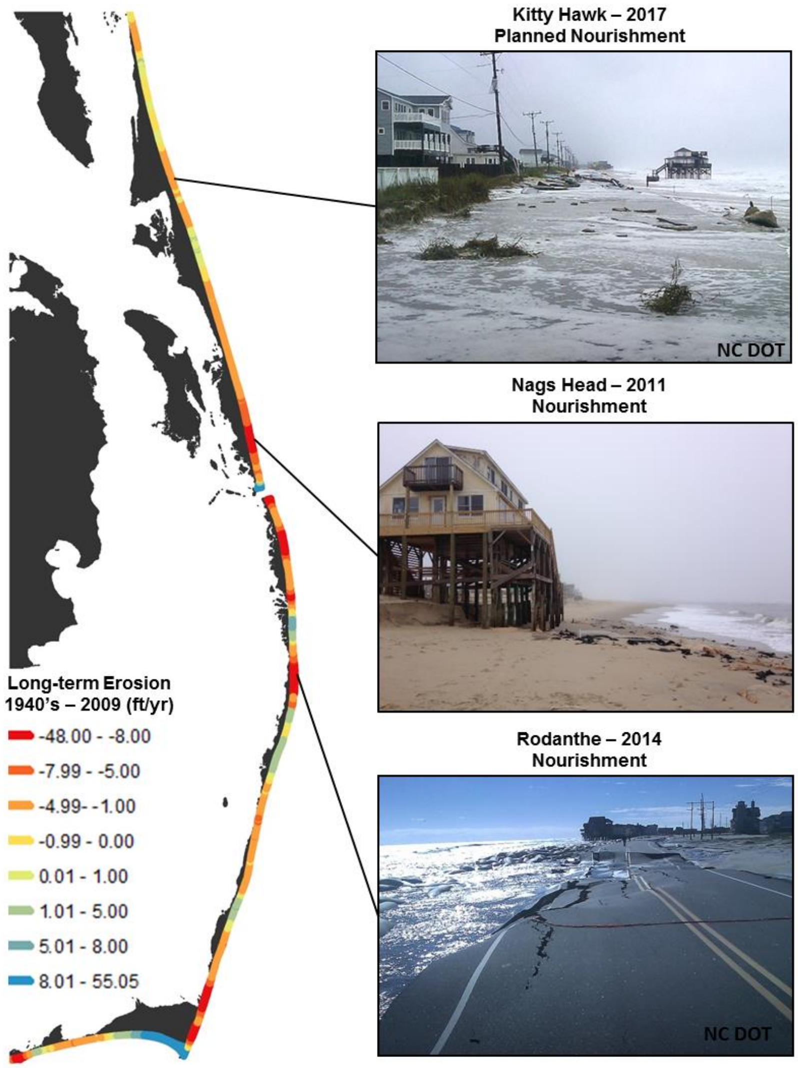

Fig. 2. Long-term ocean erosion rates for Dare County from the NC Division of Coastal Management (2012). Note the erosional hotspots (photos) at Kitty Hawk, South Nags Head and Rodanthe are the sites of past/future nourishment efforts.

In addition to storms, Dare County is also experiencing a high rate of relative sea-level rise (NC Sea-level Rise Assessment, Report, 2015). The USACE FRF in Duck, NC, has measured water levels since 1978. This long-term record is a key component of the NC Sea Level Rise Report (2015) and documents the fastest rise rate in the State at 0.18 ± 0.03 inches/yr over the past 36 years. To the south, the tide gauge at Oregon Inlet Marina has shown a rise of 0.14 ± 0.05 inches/yr. Both of these rates are hypothesized to increase in the future (NC Sea Level Rise Report, 2010).

Part of the aesthetic charm of the Outer Banks is its beautiful, uninterrupted beaches. This is due in large part to the lack of shoreline hardening which is prohibited by the State (with a few exceptions). Because of the legal restrictions on hardened structures, beach nourishment has been and will continue to be a widely used strategy to combat erosion.

Wrightsville Beach, in the southern part of the State, conducted the first beach nourishment in NC in 1939 (NC DCM, 2016). Since then, dozens of nourishment and renourishment projects have taken place in North Carolina, totaling over $700 million (Program for the Study of Developed Shorelines, 2016); more information is provided below. Today, beach nourishment is being considered for about 75% (120 of 160 miles) of the developed NC oceanfront shoreline (NC DCM, 2016). In the case of dune maintenance and small-scale beach projects (e.g., <50,000 cubic yards), trucked sand is economically effective (Dobkowski, 1998). However, large-scale beach nourishment projects, typically involve the dredging of sand and pumping it from offshore borrow sites (i.e., with a hydraulic dredging system). These activities have become increasingly common, and in a recent NC study, beach nourishment was identified as the preferred alternative for mitigating beach erosion (NC DCM, 2016). While beach nourishment is simple in theory, suitable sediment, i.e., material that is compatible with the natural beach, is not ubiquitous offshore. Thus, project costs fluctuate with proximity to the borrow area and shore and costs are also dependent on the geological nature of the borrow source and the efforts needed to extract the beach quality sand (Dobkowski, 1998; Leatherman, 1989). With limited sand resources, regional sediment management is a strategy highlighted by the U.S. Army Corps of Engineers (http://rsm.usace.army.mil/), and in keeping with this management philosophy, use of navigational dredged material should be considered when possible.

Despite the wide use and reliance on beach nourishment, there is no centralized information source for existing data regarding potential offshore sand sources. After Hurricane Sandy in 2012, the Bureau of Ocean Energy Management (BOEM) funded thirteen East Coast states (including NC) to compile pertinent data and knowledge, with particular focus on federal waters (the Outer Continental Shelf or OCS) to fill this information gap and create efficiencies for states seeking beach nourishment materials. ***The objectives of this report are to: 1) evaluate the nature of erosion in Dare County based on long-term erosion rates and relate it to past and future nourishment demands, 2) summarize the availability of geophysical and geologic data in federal waters from 3 to 8 nm, and 3) revaluate data for potential nourishment borrow sources offshore Dare County.***

Methods

Shoreline change data was obtained for a ≥60-year period (~1940s to 2009) from the NC Division of Coastal Management (NC DCM); these data were calculated from georeferenced historical aerial photos using the end-point method and the Digital Shoreline Analysis System (NC DCM, 2012). At East Carolina University and the UNC Coastal Studies Institute, ArcGIS was used to produce maps of shoreline erosion and accretion (e.g., Fig. 2). To better understand the magnitude of sand loss, total subaerial and subaqueous eroded sediment volume was calculated for the specified period using the average long-term erosion rate (from 2,754 DCM transects), the transect spacing and a volume estimator (16.4 yd^3/yd^2). The initial year of the analysis period ranged from 1940 to 1949 because of the availability of aerial photography. The volume estimation parameter (16.4 yd^3/yd^2) is described in Inman and Dolan (1989) and is based on the equilibrium profile concept. While this method has limitations due to morphological and process variability and does not consider short-term changes, it is anticipated to be reasonably accurate over a large temporal and spatial scale.

To evaluate offshore sand resources, existing data and borrow information from different sources was employed (Fig. 3). For more insight, the regional U.S. Geological Survey (USGS) data were compared with the high-resolution design and reconnaissance sub-bottom data obtained from Coastal Planning and Engineering (CPE; now part of CB&I). Sand thickness horizons from CPE spaced at ~100 ft were exported from Chesapeake Technology's SonarWiz processing software to ArcGIS points for the northernmost survey site near Duck, NC (Fig. 3). These data were compared with information from USGS Chirp tracklines conducted in 1999 spaced at ~1000 ft

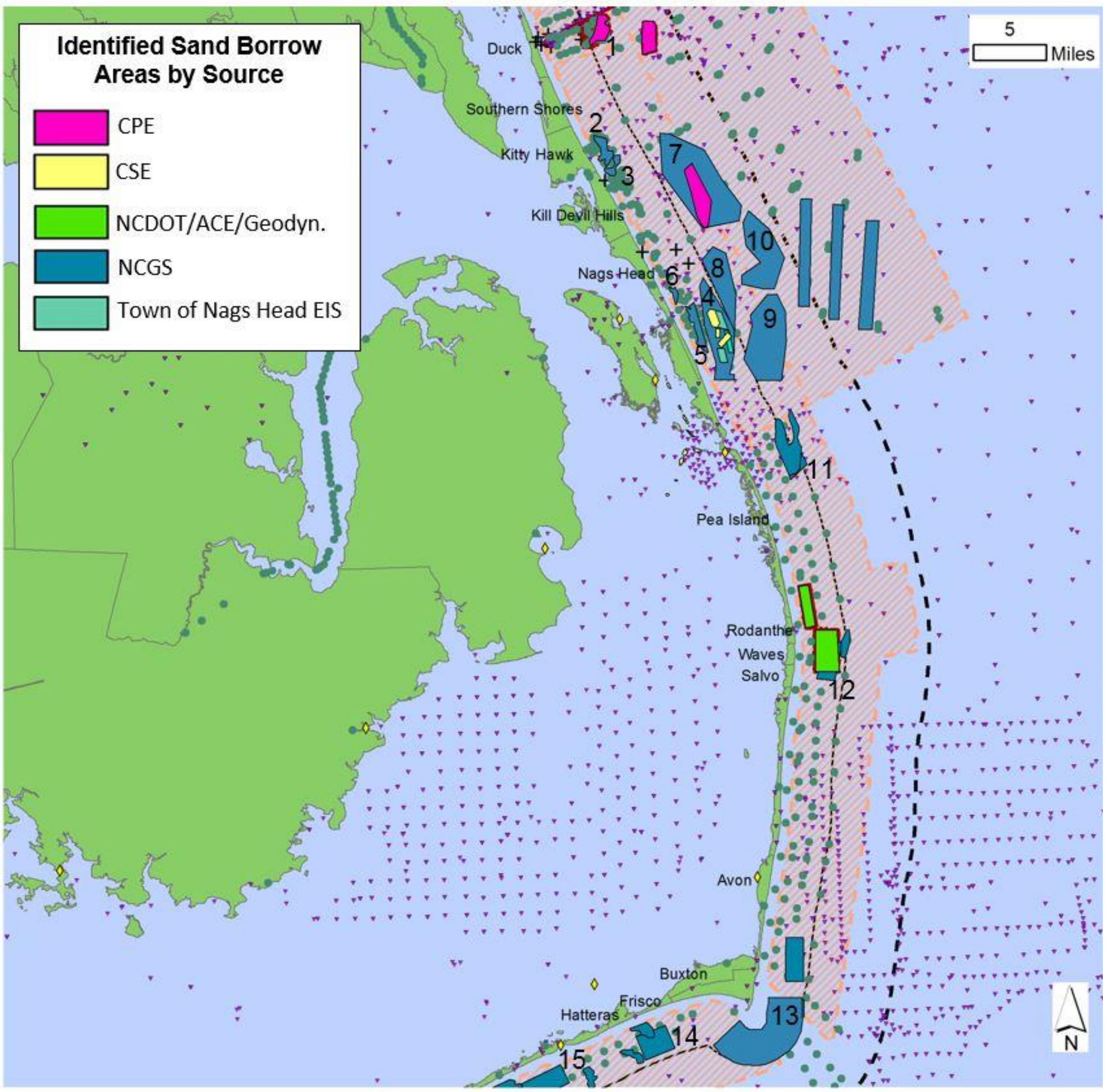

Fig. 3: Identified potential borrow areas in Dare County. Color coding indicates identifying source.

(Thieler et al., 2013) by identifying 266 intersection points using ArcGIS. Estimated "modern" sand thickness from the USGS isopach and the CPE horizons were associated with each point. Since the USGS dataset was coarsely gridded (i.e., 500 ft isopach grid cells), the USGS isopach raster was resampled into 42 ft cells, and a 245 ft buffer was created to determine a mean thickness value at each intersection point with the Zonal Statistics tool. With approval from NC Division of Transportation (NC DOT) and the USACE, a comprehensive dataset of seismic, bathymetry, sidescan sonar, vibracores and remotely acquired video ground truth in the vicinity of Wimble Shoals (near Rodanthe; Figs. 1 and 3) was also obtained from Geodynamics LLC and analyzed in a similar fashion.

Erosion and Related Economic Considerations of Dare County

As noted above, much of the Dare County ocean shoreline has experienced long-term erosion (Fig. 2). Rates of change vary from localized accretion, such as along the northern shoreline of Oregon Inlet to substantial loss, e.g., >8 ft/y in several locations (Fig. 2). The variable erosion rates across the County are impacted by the underlying geologic framework and transport processes (Riggs et al., 1995; McNinch et al., 2004; Miselis and McNinch, 2006; Thieler et al., 2014). Specific areas of high erosion, often called "erosion hotspots", are found in Duck, Kitty Hawk, northern Kill Devil Hills, southern Nags Head, Rodanthe, and Buxton (Fig. 1). Because of chronic erosion and a few recent strong storms (including Sandy), several towns have conducted or are planning nourishments. Erosion data for the towns are in Table 2.

Table 2: Erosion information for Dare County towns involved in beach nourishment. Time interval for erosion assessment was 60+ years. See text for details.

Town	Avg. Shoreline Change Rate (ft/y)	Max Shoreline Change Rate (ft/y)	Total Sand Volume Lost Over Time (yd^3)	Avg. Annual Sand Volume Lost (yd^3)
Duck	-0.5	-2.4	2,012,934	29,175
Kitty Hawk	-1.9	-3	4,394,700	63,694
Kill Devil Hills	-0.4	-4	1,296,047	18,788
Nags Head	-3.4	-10.9	19,124,091	314,231
Dare County	-1.9	-10.9	99,897,609	1,591,003

A volumetric analysis of sand loss due to erosion is employed here to place nourishment efforts in a broader perspective. Based on the long-term average erosion rates, Dare County has lost roughly 100 million yd^3 in volume over the 60+ year period (i.e., from the exposed and submerged beach). This amounts to 1.6 million yd^3 annually. Duck, Kitty Hawk, Kill Devil Hills and Nags Head have lost 2,012,934 yd^3, 4,394,700 yd^3, 1,296,047 yd^3, and 19,124,091 yd^3 over the 60+ year period, respectively (Table 2). Indeed, much of these losses are in concentrated areas, and it must be highlighted the beaches are typically managed to consider the "system" as a whole, considering both the updrift and downdrift areas. A major concern about beach erosion, and thus an argument in support of beach nourishment, is the potential loss in economic revenue.

Dare County is an important economic engine, generating over a billion dollars in tourism annually (Economic Development Partnership of NC, 2016). According to data from the Outer

Banks Visitors Bureau, Dare County accumulated over $414 million in occupancy receipts in 2014 (Table 3). Hatteras Island (i.e., the towns from Rodanthe to Hatteras, Fig. 1) accounted for over $114 million, or 28% of the County total. From this revenue, the State of NC receives 6.75% in sales tax (~$28 million in 2014), and the County receives a 6% occupancy tax (~$25 million in 2014). Of the 6% collected by the County, one third (i.e., 2% or ~$8 million in 2014) is added to a shoreline management fund for potential beach nourishment, vegetation planting, sand fencing and dune building projects and related planning. Additional tourism value related to beaches includes tourism expenditures including shopping and services; data are not available for all of these revenues. However, meal receipts in 2014 totaled $225 million in the County. The State received 6.75% in sales tax ($15 million), and the Dare County Tourism Board received 1% ($2.25 million) primarily to promote tourism and administration. Beaches are undoubtedly an important draw for visitors.

Table 3: Occupancy and receipts in 2014. Citations in text.

	2014 Occupancy Receipts $	% Total	2014 Meal Receipts $	% Total	2014 Beach Fund $
Avon	35,374,915	9%	8,839,405	4%	707,498
Buxton	10,176,061	2%	7,670,914	3%	203,521
Colington	657,055	0%	2,127,409	1%	13,141
Duck	75,317,724	18%	25,001,355	11%	1,506,354
Frisco	9,238,825	2%	1,379,837	1%	184,777
Hatteras	17,952,234	4%	4,124,449	2%	359,045
Kill Devil Hills	64,058,766	15%	57,739,397	26%	1,281,175
Kitty Hawk	25,745,222	6%	32,643,143	15%	514,904
Manteo	5,882,482	1%	12,237,836	5%	117,650
Manteo - Outside	207,008	0%	3,501,892	2%	4,140
Nags Head	106,251,783	26%	59,424,975	26%	2,125,036
Rodanthe	16,081,370	4%	3,043,573	1%	321,627
Salvo	15,111,343	4%	115,830	0%	302,227
Southern Shores	21,679,643	5%	4,588,020	2%	433,593
Waves	10,488,967	3%	2,493,107	1%	209,779
TOTAL	**414,223,398**	**100%**	**224,931,142**	**100%**	**8,284,468**

Dare County Nourishment History and Costs

The first large-scale beach nourishment project was completed in 1973 in Dare County near Buxton (Fig. 1). Twenty-six nourishment episodes have followed, with the majority occurring through dredge disposal from Oregon Inlet to Pea Island (Table 4). Excluding the Pea Island activities, projects have ranged significantly in size and cost, from just under 1 million cubic yards to nearly 5 million cubic yards and $11 million to almost $50 million. A per yard cost comparison shows sand expense ranged from $8 to $13 per cubic yard, which is consistent with projects elsewhere in NC and other U.S. states (Trembanis et al., 1999; Program for the Study of Developed Shorelines, 2016). The 2011 project at Nags Head ($37.3 million; Table 4) was, until that time, the largest entirely locally funded project in the Nation; it was paid using a combination of property taxes and aforementioned revenue for shoreline management from Dare

County occupancy tax (Town of Nags Head, 2016). This nourishment effort is viewed by many in the community as successful; the enhanced beach-dune system endured a few strong hurricanes (Irene, Sandy and Arthur) and many other storms. In 2015, Coastal Science and Engineering reported that ~85% of the sand remains within the system, yet an historical erosional hotspot in South Nags Head has lost a considerable portion of its nourished sand (i.e., 65% of the nourished sand sand lost in Reach 4; Coastal Science and Engineering, 2015).

Table 4: Information on Dare County beach nourishments (Program for the Study of Developed Shorelines, 2016).

Location	Year(s)	Total Volume (m^3)	Cost (Normalized $)	Cost per cubic yard $
Duck	2017	1,061,200	14,589,000	14
Kitty Hawk	2017	1,913,000	18,440,000	10
Kill Devil Hills	2017	914,800	10,008,000	11
Nags Head	2011	4,600,000	37,344,398	8
Pea Island	1990, 1991, 1992, 1993,1995,1996,1997, 1998,1999,2000,2001, 2002,2003,2004,2013	7,747,902	29,611,318	4
Rodanthe	2014	1,620,000	20,422,535	13
Buxton	1966, 1971, 1973, 2017	4,412,000	46,390,374	11
Hatteras	1974, 1977,1984, 1986,1988,1992,2003	887,801	11,825,429	13
TOTAL		**23,156,703**	**188,631,054**	**8.1**

The towns of Duck, Kitty Hawk and Kill Devil Hills are planning a major ~$43 million combined nourishment effort (listed individually in Table 3) to start during the dredging window of 2017. This work is also being locally funded by the Dare County shore protection funds as well as town increases in property taxes implemented through municipal service districts (See the Dare County website, http://www.darenc.com/beachnourishment/ with links to town web sites for details). The collaborative nourishment project is especially advantageous from an economic perspective as dredge mobilization costs are reduced.

Offshore Data Availability

Because of ongoing erosion and related economic concerns, there is strong motivation for beach nourishment in Dare County. As a result, there is much need to understand offshore sand resources. To obtain even a general idea, this requires geological and geophysical data, including information on the bathymetry, stratigraphy and sediment properties. While a variety of field efforts have obtained these types of data over the years offshore of northeastern NC (Fig. 4), there are gaps in coverage (e.g., areas lacking cores) and limits to the quality of existing data (e.g., resolution of bathymetry and seismic data). Furthermore, it is the widespread and integrated datasets (i.e., with large data amounts and multiple data types) that help provide the clearest perspective on sand availability, such as that by the USGS (Thieler et al., 2013, 2014; Fig. 5).

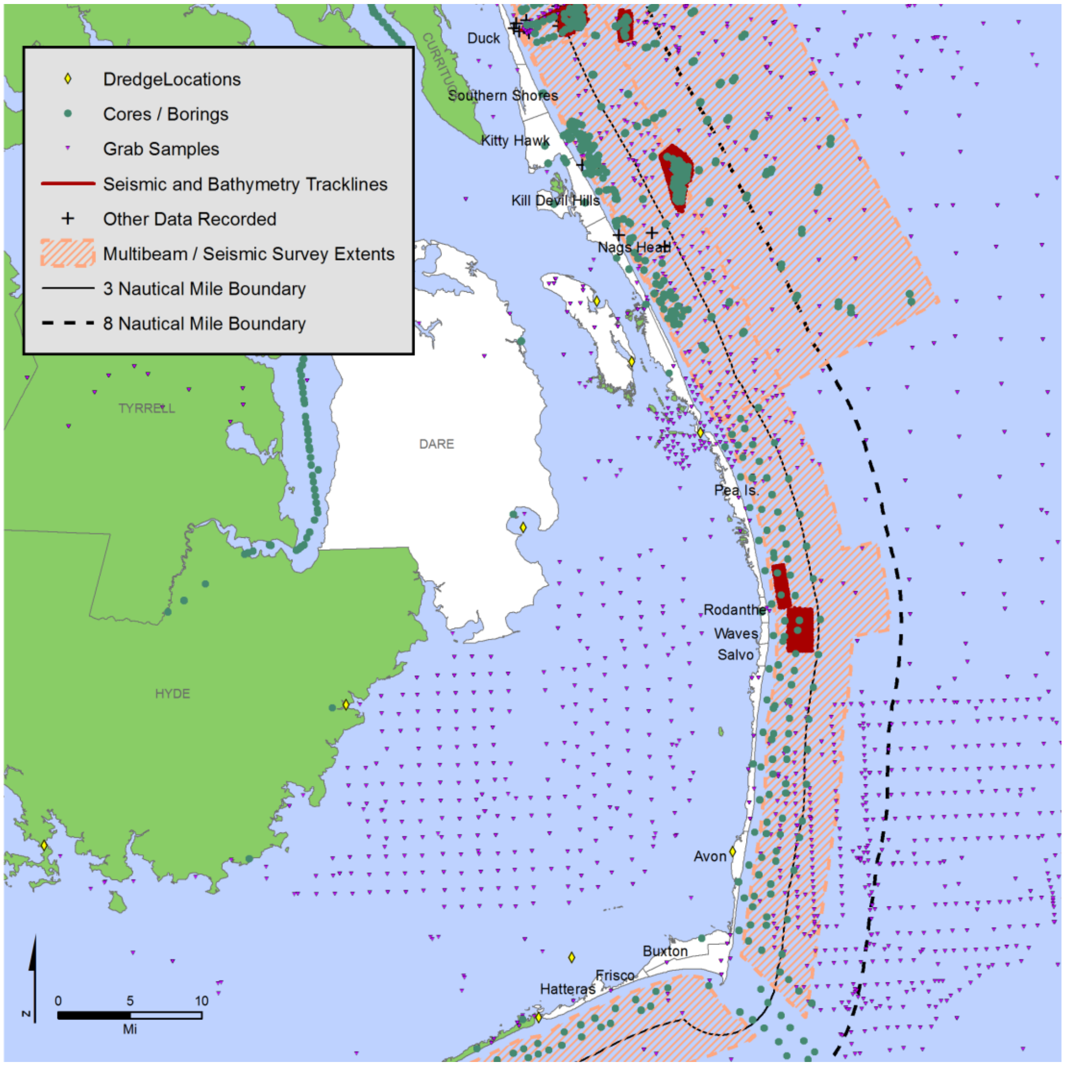

Fig. 4. Offshore geological and geophysical data.

Several datasets are of particular importance due to their quality and spatial or temporal coverage. Beginning in 1999, Stephen Boss (University of Arkansas) in collaboration with Charles W. Hoffman and the North Carolina Geological Survey prepared several publications on sand availability using reconnaissance from a suite of geophysical, geologic and bathymetric data (see Boss et al., 2002; Boss and Hoffman, 2000, 2001 and references therein). This work was largely conducted within 3 nm (i.e., State waters) for the Outer Banks Task Force and the NC DOT. At the time, Dare County was considering nourishment, but the first project did not begin until ten years later likely due to resource availability, the complexity of funding structures and permitting. These data were important to the BIMP report (2011). Based on high-resolution single-channel seismic data and 121 vibracores (up to 20 ft in length), six potential sand sources were identified, ranging from 11 to 70 million cubic yards.

A large-scale cooperative geological research effort (involving academic, State and federal entities) was conducted across coastal northeastern NC, including a substantial effort along the inner shelf in the 1999-2005 period. Thieler et al. (2013) released the U.S. Geological Survey Open-File Report 2011–1015 which used a similar suite of data over ~5400 line miles covering an impressive 1000 mi^2 area) from the Virginia border to Ocracoke with seismic grid lines extending ~6.2 nm offshore (Fig. 5). The seismic reflection data in this work, acquired by Chirp and Boomer instruments, was of varied quality. This cooperative research program examined the geologic framework, processes, and evolution of the barrier-island system which are critical to effective management of this dynamic coastal system; a great number of publications resulted (e.g., Riggs et al., 2009; Thieler et al., 2014 and many referenced therein). The modern sediment (dominantly sand) thickness isopach map (Fig. 5, discussed in later section) and the regional geological assessment are valuable products for offshore sand resource assessment (Thieler et al., 2014); unfortunately, a similar-scale research effort has not been conducted south of Cape Lookout, i.e., southern NC.

Two datasets collected by private companies in recent years provide a great comparison to the USGS data. CPE (2014) was contracted by the Towns of Duck, Kitty Hawk and Kill Devil Hills to complete a comprehensive marine sand search investigation and borrow area design. High-resolution geophysical surveys were conducted including sub-bottom profiling at 100 ft spacing, sidescan and bathymetry (CPE, 2014). In addition, historic beach shoreline and volume change studies were undertaken using data from the USACE and BOEM. This nourishment, which was originally planned for 2016, has now been delayed until 2017 due to limited dredge options.

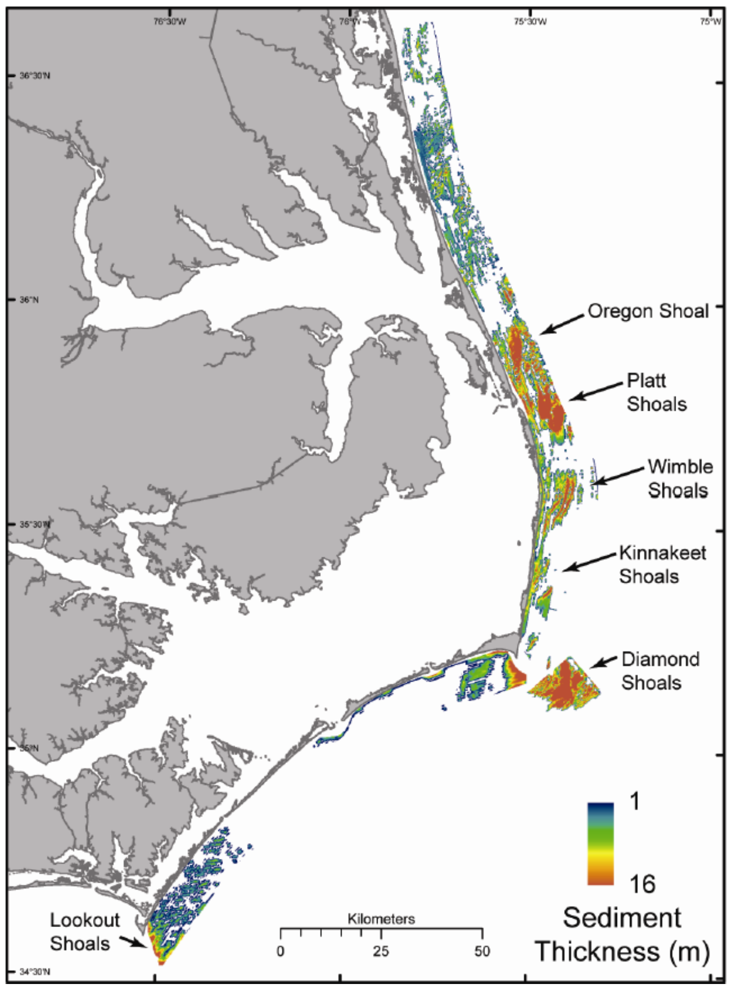

Fig. 5: Sediment thickness map from Thieler et al., 2013 2014. Note data extend ~6.2 nm offshore.

Another important study was completed in 2013 for the NC DOT and USACE by Geodynamics; work was located 0.5 to 3 nm offshore the “S-turns” erosional hotspot just north of Rodanthe, NC (Fig. 1). High-resolution multibeam bathymetry, multibeam backscatter, sidescan sonar and Chirp seismic surveys were conducted at two target sites covering a total of 5.2 nm^2 (Geodynamics, 2013). Chirp sub-bottom data were collected at 1000 ft spacing and used to create modern sand thickness isopach maps. All remotely sensed data was ground truthed using high-definition video acquired with a remotely operated vehicle, and results were combined to identify potential hard bottom habitats and any cultural resources within and surrounding the potential borrow area (Geodynamics, 2013).

Additional offshore data exist from localized and broader-scale efforts (e.g., Boss and Hoffman, 2000). These other data will not be discussed here, but information about this and related research can be obtained in Walsh et al. (2016).

Offshore Borrow Sources

Based on a combination of reports (e.g., BIMP, USGS, CPE and NC DOT), 27 potential offshore sand borrow sources are identified near Dare County, with some that are overlapping (Fig. 3); most of the larger zones are associated with sand ridges or shoal complexes (Figs. 1, 3 and 5). Design-scale seismic-reflection data and cores are needed in most areas to assess if these potential areas contain sufficiently thick and compatible sand, but existing data suggest most are good possible sources. Of the 27 identified, one dataset, the CPE borrow area C (ID#1 in Table 5), has a detailed volume estimate based on design-level surveys. CPE borrow source A is not included here due to overlap with OCS1 (in Table 5). The 14 other potential sources have very rough estimates of sediment volume totaling roughly 2.3 billion cubic yards (Table 5). Note that the phrasing "sediment volume" is used here deliberately as the percentage of sand is not known in most of these locations. Focused studies, such as the research conducted by Geodynamics and CPE, are required to refine these gross estimates. High-resolution surveying and extensive coring are critical to determining the exact

Table 5: Rough sediment volume estimates (in millions of cubic yards) for specific borrow sources (See ID# in Fig. 3). *Denotes BIMP (2011) lists only 11yd^3 which is a fraction of the portion in State waters. [&]"OCS" added to indicate Outer Continental Shelf.

ID# (Fig. 3)	Borrow Area Name	Sediment Volume (millions in yd^3)	Reference for Volume Estimate
1	Area C Duck	2.7	CPE, 2014
2	N1	5.2	USACE, 2000
3	N2	2.4	USACE, 2000
4	S1	104.5	USACE, 2000
5	S2	7.2	USACE, 2000
6	S3	1.4	USACE, 2000
7	OCS1[&]	173.5	Boss and Hoffman, 2001
8	OCS2[&]	44.9	Boss and Hoffman, 2001
9	OCS3[&]	64.7	Boss and Hoffman, 2001
10	OCS4[&]	23.2	Boss and Hoffman, 2001
11	N. Pea Is.	68.5	Boss and Hoffman, 2000
12	S. Pea Is.	55.9	Boss and Hoffman, 2000
13	Diamond Shoals*	1660	Boss and Hoffman, 2000
14	Hatteras Village	28.5	Boss and Hoffman, 2000
15	Ocracoke	70.1	Boss and Hoffman, 2000
Total	-	2312.7	This study

spatial extents of a particular borrow site, the geological composition of the site (e.g., sand overlying mud, rock extent) and whether the sand is compatible with the intended beach. Nevertheless, because of the broad extent and relatively high detail of the USGS data (Thieler et al., 2013; 2014), these data and resulting interpretations can be very helpful in refining the best possible locations for detailed surveys. To put this another way, the USGS data may be useful for pinpointing areas of sand resource potential.

Comparison of USGS Isopach With Other Studies

To help evaluate how the regional-scale, more widely spaced USGS data can be used to narrow down potential borrow sites, the interpreted USGS modern sediment isopach (Fig. 5) was compared to the survey-scale data of CPE near Duck, and Geodynamics near Rodanthe. The USGS sediment isopach map offshore Duck demonstrates that sediment cover is quite thin, only in a few areas does it exceed 6 ft, such as where CPE conducted its detailed survey (Fig. 6).

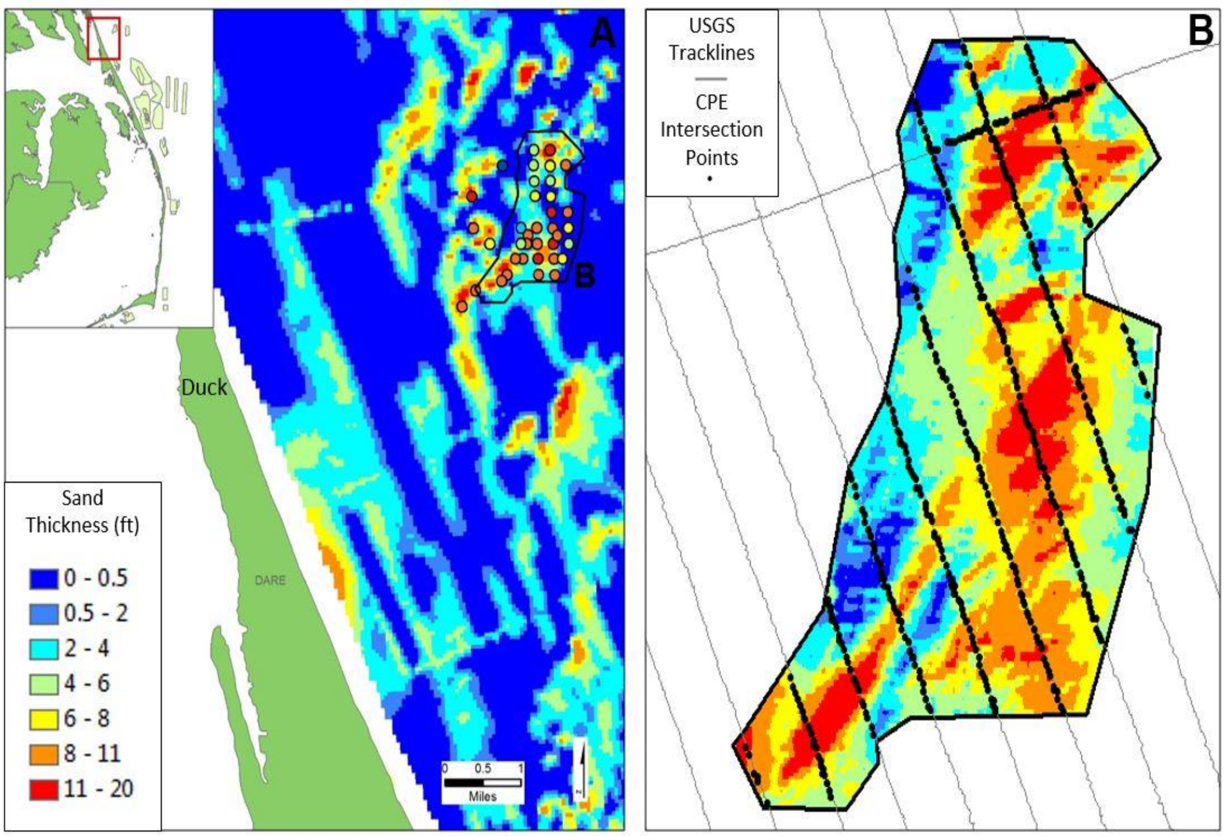

Fig. 6. CPE core points and sand thickness overlain on the USGS modern sand isopach (Panel A). CPE sand isopach and the points at trackline intersections used for comparison (Panel B).

Sand thickness in CPE cores shows some consistency with the USGS isopach (Fig. 6A). Qualitatively, it can be seen that the CPE sediment thickness data is generally consistent with the isopach of the USGS (Fig. 7). Deposits that reach over 11 ft in thickness are oriented in a SW-NE direction, with three foci of material. But, while the gross pattern of modern sediment cover is similar, there are substantial differences in thickness (>10 ft in places; Fig. 7, bottom right). Looking more closely at a single chirp seismic line from CPE versus the USGS isopach (Fig. 7, top), it becomes evident that the precise positioning of the seismic line relative to sedimentary deposits has a strong influence on the mapped isopach thickness (Fig. 7).

To provide a quantitative comparison, 266 intersection points in the survey data offshore Duck were determined with ArcGIS (Fig. 6, black dots on right). Here, isopach values were extracted from both datasets, and results show the USGS and CPE sediment thickness estimates differ quite substantially. Maximum sand thickness for CPE and USGS were 18.7 and 14.6 ft, respectively. The mean difference is 2.75 ft ($\sigma = 3.31$), and the two populations are significantly different (p-value $<<0.01$) according to two-sample T-test assuming unequal variances. Regression of the data (not shown) yields a R-squared value of 0.09, indicating a poor consistency between the datasets. Nevertheless, a visual comparison clearly shows a similar pattern, although the thickest locations are not perfectly co-located.

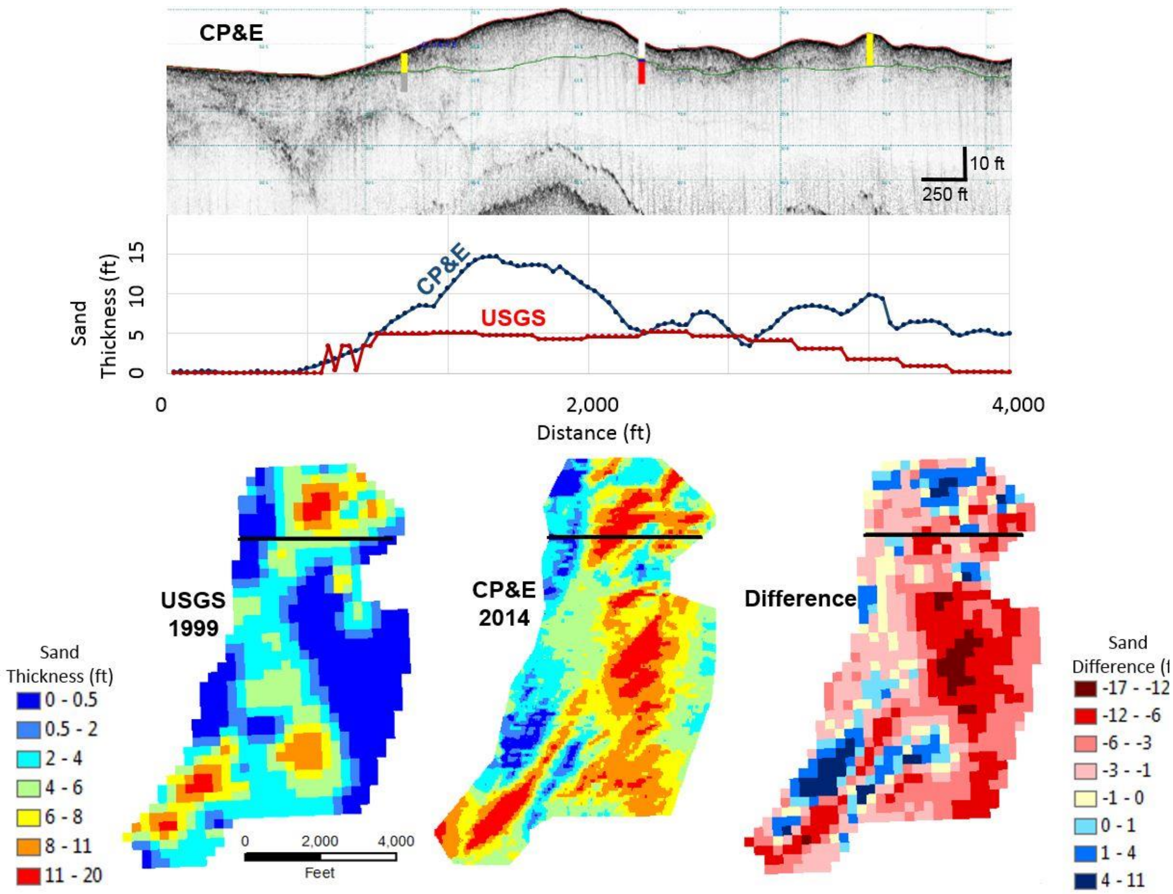

Fig. 7. Chirp seismic-reflection line across the Duck Area C borrow site overlying a graph of the interpreted modern sediment thickness from CPE and the USGS isopach (top). Sand thickness isopachs and the spatially mapped difference between them (bottom). Note, the position of the seismic line and thickness data is indicated by the black line across isopachs. The green line visible in the chirp data represents the interpreted modern sand boundary. Duck Area C is identified as #1 in Figure 3.

Similar to the observations offshore Duck, the data over Wimble Shoals collected by Geodynamics for the NC DOT and USACE also suggest a similar pattern of sediment thickness. More specifically, the sediment deposits visible in Figure 8 show a similar pattern of alignment in survey sites. For example, in subarea A, a single north-south oriented ridge is clearly present in both the USGS and Geodynamics sediment thickness data. While in B, two ridges merge to form a V-pattern. However, the magnitude of the thickness is markedly different between the Geodynamics and USGS data. Note, the coloration of the USGS data is cooler indicative of thinner deposits.

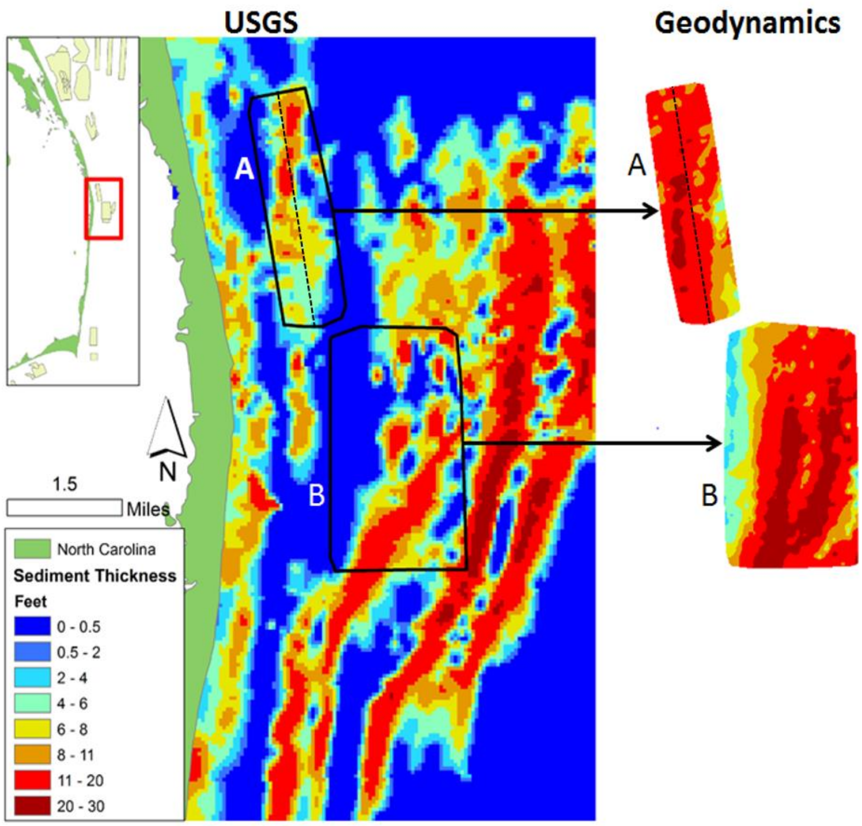

Fig. 8: Comparison of the USGS sediment thickness isopach (left) with that based on Geodynamics data (right). The latter was collected about a decade later. Dashed lines indicate the location of the seismic-reflection data in Figure 10.

Comparison of data from both isopachs at points across the area surveyed by Geodynamics (Fig.9) reveals that, where the Geodynamics data have been interpreted to have a sediment cover of 2-35 ft, the USGS results indicate only patches of sediment that are up to 20 ft thick. Regression of the observations from both datasets shows a moderate correlation ($R^2 = 0.5$) with an x-intercept of 2.9 ft, suggesting a consistent offset in the data. A visual inspection suggests an alignment of data parallel to a 1:1 relationship, and this would be expected if there was an underlying unit not mapped within one of the datasets (i.e., USGS). But, more work is needed to explore the cause for the differences between the datasets.

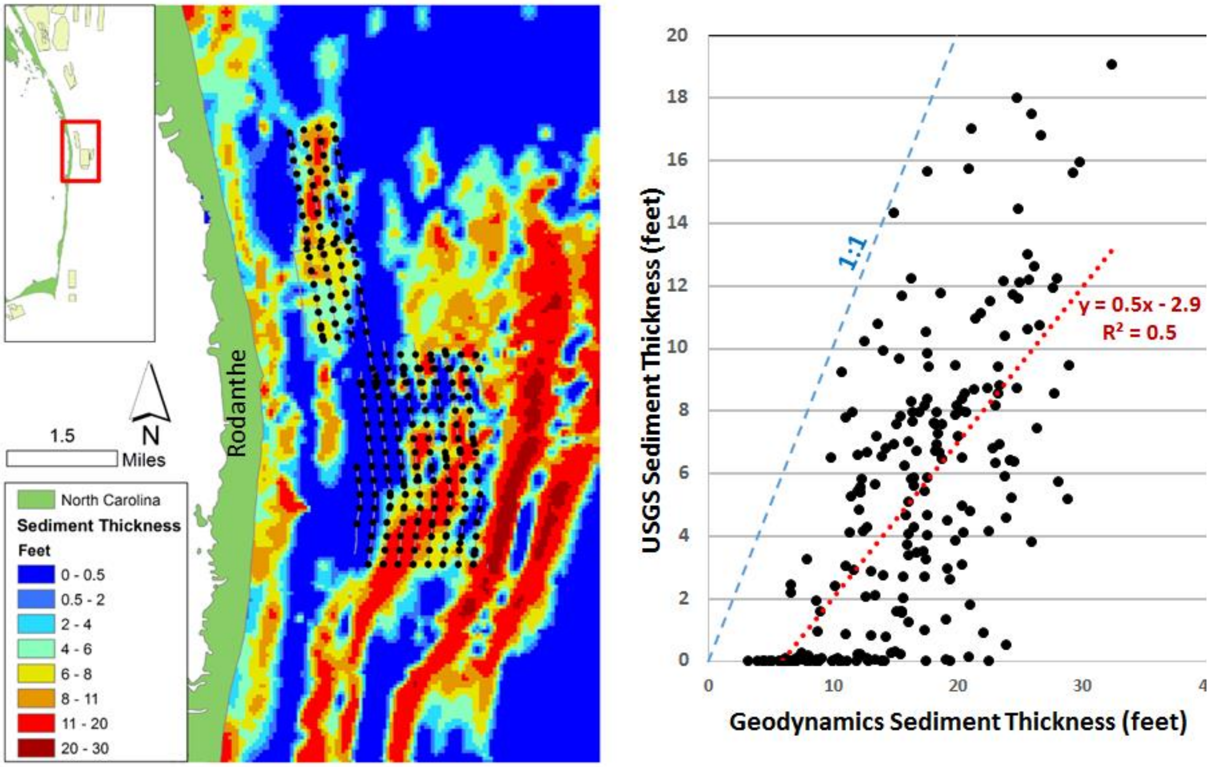

Fig. 9: Comparison points for the USGS and Geodynamics isopach data (left) and a scatter plot of the sediment thickness from these two datasets at these points (right).

Discussion

Erosion and Sand Demand vs. Source Volume for Beach Nourishment

With improved, geo-referenced aerial imagery and GIS technology, the NC DCM regularly maps the ocean shoreline position, and from this information, the net *long-term* change response can be directly assessed. Erosion along the northern Outer Banks has been ongoing at high rates (>5 ft/yr) in many areas for decades (Fig. 1); the average erosion rate for Dare County is estimated to be 1.9 ft/yr (Table 2). With strong storms and sea-level rise anticipated to continue (and potentially intensify according to some predictions), continued landward translation of the beach and shoreface is expected in the future. Based on the long-term shoreline movement and assuming the maintenance of similar profile, the County loses nearly 1.6 million yd^3 of material by the landward translation of the shoreline profile annually. Several towns, especially Nags Head (Table 2), are consequently faced with persistent erosion management challenges. Much research has focused on the driving factors and potential future changes, but a complete discussion of this is beyond the scope of this paper. Some recent papers discuss storm erosion responses (List et al., 2006), regional gradients in transport due to shoreline curvature (Lazarus and Murray, 2011), control of nearshore stratigraphy (Miselis and McNinch, 2006) and nourishment frequency (McNamara and Keeler, 2013; Smith et al., 2014). A typical approach to understanding the potential behavior of a coastal sedimentary system is to use a sediment budget (e.g., Bowen and Inman, 1966; Komar al., 1996; Rosati et al., 2005). Inman and Dolan (1989) employed this approach to estimate that, for the whole northern NC ocean shoreline, erosion is a function of overwash displacement (39%), transport out of the system (22%), wind advection (18%), inlet sequestration (10%), and removal by dredging (11%). Using new data, the authors suggest a refined sediment budget be calculated to better define the driving processes of change today and into the future. Regardless, oceanfront erosion continues across much of Dare County, and in some areas at relatively rapid rates.

Because of erosion, there is a clear need for sand to enable nourishments. Although localized, the amount of sand potentially available offshore is sizable. Based on rough estimates of 15 of the potential source areas, 2.3 billion cubic yards are present (Table 5). Using this information and assuming a need to nourish every five years at a similar volume of recent /planned projects (~13 million cubic yards; Table 4), there is theoretically enough volume to last ~900 years. Instead, if we calculate need based on the annualized eroded volume, there is potentially enough offshore to last ~1500 years. However, as outlined above, there are variables still poorly understood with these potential borrow areas such as the quality of material, non-beach-quality overburden and accurate spatial extents. All these factors are critical to consider, especially from a cost perspective. Sand shortages in some areas are inevitable because of the inhomogenous distribution of sand offshore, and sand needs will probably increase with time because of continued sea-level rise, storms, and development.

It must also be emphasized that the potential offshore sand volumes listed in Table 4 are inevitably an overestimate because most of these areas have not been surveyed and/or sampled at a design scale. The USGS data can help provide better estimates, but ultimately a suite of high-resolution data is needed to help determine the spatial distribution and total amount of beach compatible sand. Regardless, borrow area assessments can be high for several reasons. Some areas will be precluded from usage for being too thinly covered by sediment; deposits must be sufficiently thick for a buffer during dredging. Also, the potential impact on ecologic and cultural resources must be considered and avoided where possible. Possibly the greatest concern is the sediment itself. Deposits are not likely to be 100% suitable sediment. The compatibility of nourishment sediment is determined by the NC technical standards for beach fill (NC DCM, 2013). For example, for the planned joint project in Duck, Kitty Hawk and Kill Devil Hills, CPE pursued another (a third) offshore borrow site (most eastern site offshore Duck shown in Fig. 3), but after closer examination with sub-bottom and core collection, the usable sand layer was thinner than expected (i.e., <3 ft) and consequently this potential source was removed from consideration (CPE, 2014). This is one of many examples in which potential borrow areas can be excluded from usage, and as a result of situations like this, the costs associated with identifying and transporting sand for nourishments is variable (Table 4). This further highlights the need for better and more spatially dense sand resource data in advance of the need.

Economic Considerations of Beach Nourishment

This discussion is not meant to provide a complete or even comprehensive account of the many economic considerations of coastal community revenues and the financial specifics of beach nourishment. For more information, the reader is directed to the Dare County website (http://www.darenc.com/beachnourishment/), the USACE (2000) and the BIMP (2011) for NC-related analyses, and for a broader perspective, consult the Heinz Center report (2000). But, some general data are provided here to help provide a fiscal perspective on the matter of erosion, including the mitigation of erosion and the overarching economic impacts where beach tourism plays a major role in revenue generation. In total, a combination of Dare County and municipal funding has been/will be used to cover ~$100 million dollars of beach nourishment from 2011-2017 in Nags Head, Duck, Kitty Hawk, Kill Devil Hills and Buxton (north to south, Fig. 1). The projected "lifespan" of these projects, based on statistical and theoretical engineering models, have different estimates ranging from 5-10 years. However, it should be noted that these models typically assume time-average erosion rates and have limited accuracy predicting the lifecycle of an engineered beach due to the impossibility of knowing the future occurrence of powerful hurricane and nor'easter storms. Assuming these project investments last ten years, this cost represents a minute (~1%) portion of the billion-dollar tourism industry (per year) for Dare County over a 10-year period, and the success of this industry hinges on robust beaches. Moreover, the County has taken a responsible, proactive approach by collecting taxes to cover nourishment costs as federal dollars for beach projects has dwindled. Over a 10-year period, occupancy tax revenue (based on 2014 data) for beach projects is estimated to be ~$83 million dollars. This estimated revenue is comparable to the recent expenditures (i.e., $100 million). However, if similarly sized repeat nourishment projects are needed at all sites in less than 10 years, or if new projects are required elsewhere, additional support may be needed, although it seems likely that conditions and costs will change with time.

Offshore Data Availability and Utility

Based on previous efforts, including those by the State, federal agencies and private industry, it is clear that there is a good handle on potential sand sources offshore northeastern NC. With multiple known borrow sites in Dare, there is apparently sufficient supply for decades. However, the cost of obtaining sand for a project will depend on the proximity of sufficiently compatible sand and the variable costs of dredging (among other things). As demands for replenishment persist and potentially increase, the closest and most affordable borrow sources may be exhausted requiring the use of sources farther from the project site or more offshore. With the caveat that more work is needed to refine these potential sand sources, the largest borrow source data gap (Fig. 3) is evident offshore Duck where only one relatively small deposit (2.7 million yds^3) has been identified. There are more plentiful sources about 10 miles south. An extensive ~15 mile gap in data also exists between Salvo and Avon, but fortunately along the entire Dare coast, there are core and seismic reconnaissance data to aid in the identification and development of potential future sources in this region.

One related concern is that there is a poor understanding of whether or not borrow sources will regenerate after being dredged. Almost no data exists on the recharge rate for borrow areas following dredging events. The importance of these data cannot be overstated as it has implications on long-term mining at each location. The authors suggest, that larger projects be required to conduct bathymetric monitoring of the borrow site immediately following the dredge event and potentially after the forecast half-lifespan of the project (i.e., 5 years for a 10-year project). While this will increase project costs, it will provide a much-needed understanding of the sustainability of the borrow source, potentially saving future costs.

Dare County is fortunate to have a good amount of geological and geophysical data offshore (Fig. 4) and is arguably the most understood nearshore system in the State. In particular, the USGS dataset presented in Thieler et al. (2013, 2014) is invaluable for preliminary sand resource identification and assessment and has and will continue to provide reconnaissance-level insight to maximize the efficiency in borrow source development (a costly and time-consuming process; see State of NC, 2013). As noted, results appear to generally agree with the mapped strata by CPE and Geodynamics, with similar trends of increasing and decreasing sand thickness (Figs.7-9). However, there are many contradictory observations between the USGS and the other estimates with high-resolution data, in some cases up to a 23 ft difference was seen. The sand thickness appears to most often be a lower amount by the USGS, potentially an underestimation. (Fig. 9). For example, peak sediment thicknesses over Wimble Shoals, reach 30 ft by Geodynamics whereas USGS estimates do not exceed 20 ft.

There are several factors potentially responsible for the differences among the datasets. First, due to the ~15 year difference between data collection, some mobilization and transport may have occurred, especially associated with large storm events like Isabel (2003), Irene (2011), Sandy (2012) and Arthur (2014). Thieler et al. (2014) measured southward transport of sands within Wimble shoals dating back to the late 19th Century. A second consideration is that the USGS data is more coarsely spaced than the design-level seismic-reflection and core data collected by Geodynamics and CPE which may also result in differences. For example, one survey may cross a sedimentary peak while another only transited an adjacent ridge or valley (e.g., Fig. 10). Horizontal positioning offsets (up to 30 ft) can also result in mapped differences; for the regional work, the USGS used Differential GPS positioning, while Geodynamics (and potentially CPE) used more precise survey-grade GPS. Additionally, data resolution differences between the seismic and bathymetric datasets may also have an influence (Fig. 10). Survey conditions (i.e., sea state), survey speed, instrument quality, the acoustic sound speed in water or other issues can play a role in diminishing the quality (e.g., resolution) and/or penetration of the seismic data. Finally, differences in interpretation may also serve a key role. More specifically, how a scientist maps the “modern sand” or “Holocene” sand may vary, especially in areas where data quality is reduced and/or little to no core data exist (Fig. 10). CPE and NCDOT/Geodynamics had many more vibracores to validate sand thicknesses, and this likely helped these design-scale surveys obtain a more accurate assessment of sand resource availability.

Ultimately, the USGS is a reliable dataset for evaluating potential borrow sources and a great starting point to use for further reconnaissance and potentially design-scale data collection. Closer design-scale sub-bottom line spacing and more core collection is inevitably necessary when actually planning for nourishment projects. At this time, there is sufficient knowledge on the location and volume of potential borrow sources, but adequate knowledge of the sediment characteristics within the borrow areas is lacking, and will affect the total volume of available beach-compatible sand.

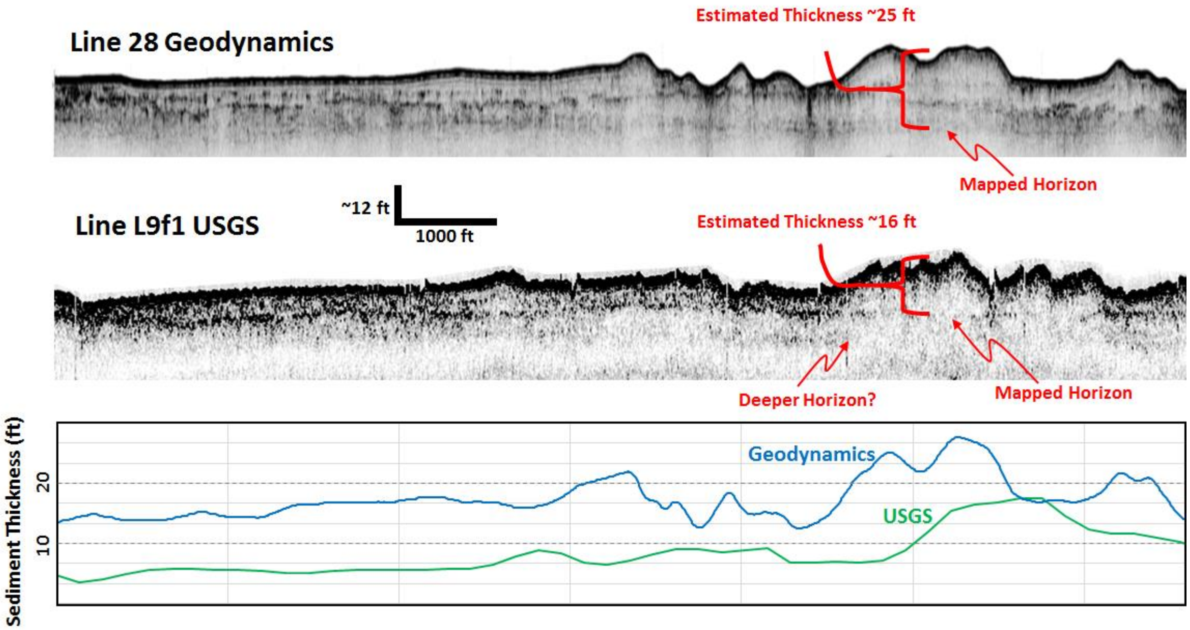

Fig. 10: Comparison of seismic-reflection data from Geodynamics (top) and the earlier USGS study (middle) along with a graph (bottom) of estimated sediment thickness along this track for both data sources (see location in Fig. 9). The lines are not exactly co-located, so some differences in the depths of the seafloor and the mapped horizons are anticipated. Note, however, that the high-resolution data obtained by Geodynamics has deeper penetration, making a deeper horizon visible. It is hypothesized that the absence of this deeper horizon in the USGS may explain the consistent difference in the isopachs for modern sediment thickness in this area (Fig. 9).

Conclusions

Dare County is one of many counties in the State and Nation that is facing coastal management challenges, which have real potential economic consequences. Erosion is widespread in Dare County, and the problem will continue and possibly increase with sea-level rise, frequent storms and continued development. Loss of land through erosion has and will continue to impact public and private property and, as a result, can affect residents and tourism-related revenues such that there is strong incentive to combat erosion with beach nourishment. Dare County and several of its towns have wisely been proactive about securing funding through various taxes to enable shore protection projects (i.e., beach nourishments). Based on the long-term erosion rates and substantial existing tourism-enhanced revenues generated from these beach-centric communities, nourishment projects can and likely will continue into the future. Geological and geophysical resource data indicate sand is available in State and federal waters in isolated areas. Existing data have identified several potential borrow areas, but more work will be needed to better assess sediment volumes and compatibility as projects are planned. Discrepancies exist in the location and thickness (and thus size) of borrow areas. Monitoring of borrow areas after dredging is recommended to better understand sediment recharge for potential future use.

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