Assessing 21st Century Supply and Demand of Beach Sand Resources in the Mid-Atlantic

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RSLR	Relative Sea Level Rise
OCS	Outer Continental Shelf
BOEM	Bureau of Ocean Energy Management
ASAP	Atlantic Sand Assessment Program
DGS	Delaware Geological Survey
USACE	United States Army Corps of Engineers
ASBPA	American Shore and Beach Preservation Association
cy	One cubic yard
MEC/UXO	Munitions of Explosive Concern/Unexploded Ordnance
CNN	Convolutional neural network
SAGA	System for Automated Geospatial Analysis
NOAA	National Oceanic and Atmospheric Administration
CRM	Coastal Relief Model
NASA	National Aeronautics and Space Administration
mcy	One million cubic yards
AINS	Assateague Island National Seashore

1 Introduction

1.1 Motivation

The Mid-Atlantic coastline of the United States is one of the most populous regions of the country. It is home to thriving coastal communities, extensive military and transportation infrastructure, historical and cultural resources, habitats for many important marine and migratory species, and a major space launch facility. The regional ocean economy, including tourism, recreation, commercial fishing, law enforcement, construction, real estate, etc., represents a major component of Mid-Atlantic states' gross domestic products (MARCO 2022). However, the coastlines of this region are subject to increasing pressures of human development and relative sea level rise (RSLR), especially in areas where coastal land subsidence is occurring (Callahan et al. 2017). Increasing sea level, along with changes in coastal storm characteristics, leads to increased frequency of highly erosive storm surges (Marsooli et al. 2018, Lin et al. 2019, Pringle et al. 2021), which can result in the loss of protective beaches and dune systems and can cause significant damage to coastal infrastructure and property.

The threats posed by coastal storm surges have necessitated the adoption of coastal stabilization strategies to both fight coastal erosion and protect coastal assets. Some "hard" stabilization strategies include seawalls, offshore breakwaters, and groins, which fundamentally alter the natural landscape and coastal hydrodynamics. Conversely, beach nourishment is considered a "soft" stabilization strategy, as it seeks to maintain the structure and natural function of beach and dune systems. This is accomplished by periodically replenishing the systems with sand that is either trucked in from land or, more commonly, dredged and pumped as a slurry from navigation channels or offshore sand deposits. This has been the stabilization strategy of choice for most Mid-Atlantic coastal communities since the late 1980s and early 1990s (Elko et al. 2021).

Beach nourishment tends to be more favorably received by beach communities and tourists than hard stabilization strategies, however it is not without environmental and economic concerns (Staudt et al. 2021). While beach nourishment is generally less expensive and more aesthetically pleasing than hard stabilization strategies, it is by no means cheap, and projects must be repeated as beaches erode to maintain the protective effects against major storm surges. Additionally, the process of dredging and placing large quantities of sand represents an ecological disturbance both to the sand source (i.e., borrow area) and placement beach (Staudt et al. 2021). Care must be taken in selecting sand sources that are similar to the native beach sand and in maintaining appropriate beach slopes to minimize erosion. Extensive offshore geological assessments are necessary to ensure adequate sand quality and quantity is available, and ecological assessments are necessary to ensure that borrow areas and adjacent benthic areas are not sensitive or critical marine habitats. Additionally, the timing of dredging activities may be tailored to local ecosystems to avoid spawning and migratory seasons of sensitive species. In general, the long-term ecological and biogeochemical impacts of beach nourishment remain largely understudied (Hannides et al. 2019).

Further complicating offshore sand management efforts is the rapid acceleration of competing interests on the outer continental shelf (OCS). Designated fishing grounds, protected habitats, offshore data cable corridors, critical minerals investigations, shipping lanes, and offshore renewable energy projects all compete for space on the OCS, and these demands are likely to increase throughout the 21st century. Because of this, early planning efforts to assess beach nourishment sand demands and offshore sand resource supplies are necessary to avoid resource scarcity and potential inaccessibility in the future. Sand used in beach nourishments has historically come from borrow areas within state-managed waters (< 3 nautical miles offshore). Today, many sand resources in Mid-Atlantic state waters are either approaching depletion or have been placed off-limits due to habitat or other concerns (Warner et al. 2023). As a result, states are increasingly looking into federal waters to meet their sand resource demands. The Bureau of Ocean Energy Management (BOEM), which manages mineral and energy leases in federal waters, has recognized the pressing need for a better understanding of supply and demand for beach sand resources relative to other activities on the OCS, and it is taking action to avoid potential future resource conflicts.

1.2 Past Research Activities

BOEM has approached this management challenge through a set of cooperative agreements and contracts focused on primary data collection (e.g., reconnaissance-level vibracore sampling and geophysical surveying) and data analysis (e.g., geologic mapping and statistical analysis) in the OCS. Past efforts to map the shallow marine stratigraphy in the Mid-Atlantic have included seismic reflection surveys and sediment-coring campaigns of the BOEM-funded Atlantic Sand Assessment Project (ASAP 2015-2019), undertaken to help support beach nourishment sand needs for coastal resiliency projects in the wake of Hurricane Sandy in 2012 (APTIM 2017). The Delaware Geological Survey's (DGS) contributions to the regional collaboration between Atlantic coast state agencies and BOEM are showcased in technical reports, maps, and science papers addressing (1) general offshore geology (i.e., benthic substrate) of the Delaware inner continental shelf (Mattheus et al. 2020a), (2) the distribution of beach-quality offshore sand deposits across state and federal waters (Ramsey et al. 2016), (3) updates to the regional shallow stratigraphic framework (late Quaternary) that include maps of paleochannel locations and isopach models of Holocene sediment thicknesses (Ramsey et al. 2020, Mattheus et al. 2020b), and (4) the challenges of interpreting aggregate sediment-core datasets acquired over many decades and their integration with recent geophysical sub-bottom data (Mattheus et al. 2020c). The DGS has leveraged its offshore sediment core repository and role as primary data steward for geological information in Delaware, working with academics and other state and federal geological researchers and contributing to regional synthesis studies of late Quaternary coastal evolution (Brothers et al. 2020, Wehmiller et al. 2021, Ramsey et al. 2022). Other targeted state-level cooperative agreements across the Mid-Atlantic have addressed local concerns and helped stakeholders identify potential sand resources for near-future sand resource management activities.

In 2021, the DGS entered another cooperative agreement with BOEM to initiate a pilot study investigating long-term forecasts of sand resource demand and potential locations of additional sand resources along the Atlantic coastlines of Delaware and Maryland (Warner et al. 2023). This Technical Report and associated research aims to expand the previous study to include a larger study region from Virginia through New Jersey using similar methods for assessing long-term sand resource demand and supply at a regional scale.

1.3 Project Goals

The overall goal of this work is to support long-term coastal and offshore management by estimating sand resource demand and supply at a broad regional scale in the Mid-Atlantic United States. Specifically, this report aims to:

- Forecast sand demand for individual beaches and states under several different sea level and climate scenarios through 2100
- Assess the status of current sand sources used for beach nourishment and link them to forecasted demand
- Employ statistical methods for modeling spatial distributions of potential sand resource quality in data sparse areas
- Foster regional cooperation and collaboration on coastal sand resource management

2 Study Region and Methodology

2.1 Study Region and Geological Setting

2.1.1 Beach areas considered

This expanded study includes all Atlantic-facing beaches from Virginia through northern New Jersey. Bayshore communities in Chesapeake, Delaware, and Raritan Bays were not included. Beaches on uninhabited barrier islands (mostly in Virginia) with no history of beach nourishment were also excluded from the analysis. In total, 20 beach units were considered, some of which may include multiple independent local municipalities (mostly in New Jersey). For example, Long Beach Island, New Jersey contains the towns of Beach Haven, Long Beach, Surf City, and Harvey Cedars. Units were grouped based on recent shared beach nourishment histories and geography, and most units are clearly divided by inlets, bay mouths, park lands, or other well-defined coastal features. Table 1 describes the beach units considered in this study.

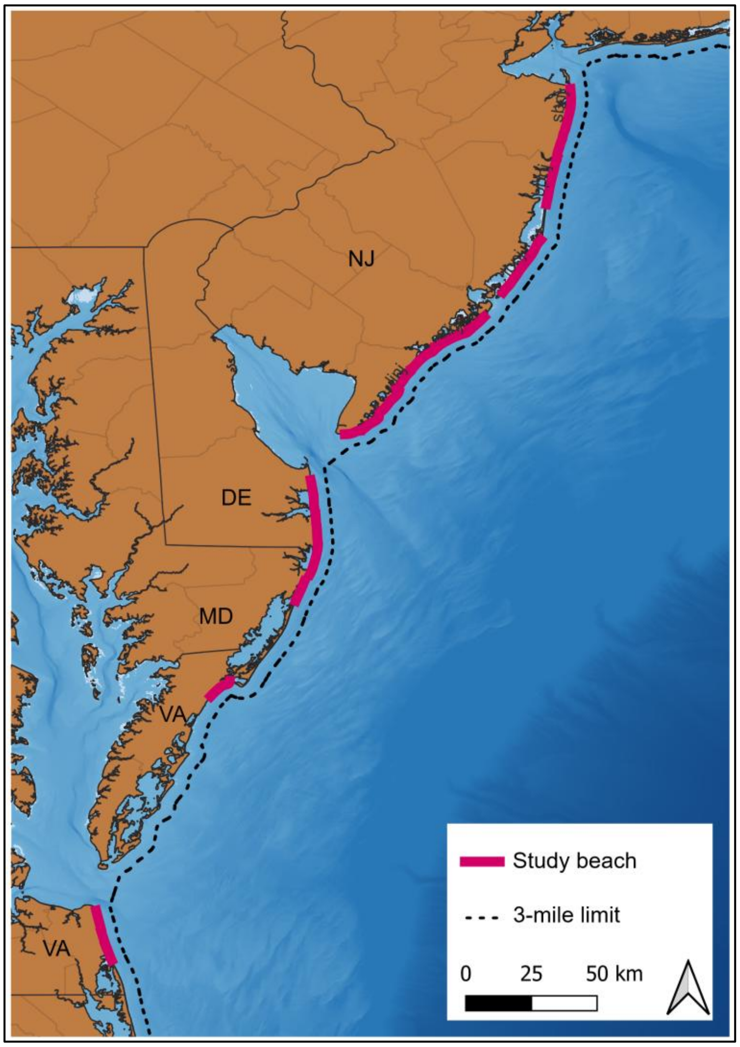

Figure 1. Study region overview
Nourished beaches included in the analysis are noted in red.

Table 1. Beach areas defined in this study and their associated characteristics
Beaches are listed from south to north.

Beach	State	USACE District	Communities, Public Lands, and Infrastructure
Sandbridge	VA	Norfolk	Sandbridge
Dam Neck	VA	Norfolk	Naval Air Station Dam Neck
Virginia Beach	VA	Norfolk	Virginia Beach
Wallops Island	VA	Norfolk	Wallops Island Flight Facility
Assateague	MD	Baltimore	Assateague State Park, Assateague Island National Seashore
Ocean City, MD	MD	Baltimore	Ocean City, Maryland
Fenwick Island	DE	Philadelphia	Fenwick Island
Bethany & South Bethany	DE	Philadelphia	Bethany Beach, South Bethany Beach
Rehoboth & Dewey	DE	Philadelphia	Rehoboth Beach, Dewey Beach
Cape May	NJ	Philadelphia	Cape May, US Coast Guard Training Center
Wildwood	NJ	Philadelphia	Wildwood
Avalon	NJ	Philadelphia	Stone Harbor, Avalon
Ludlam Island	NJ	Philadelphia	Sea Isle City, Strathmere
Ocean City, NJ	NJ	Philadelphia	Ocean City, New Jersey
Absecon Island	NJ	Philadelphia	Longport, Margate City, Ventnor City, Atlantic City
Brigantine	NJ	Philadelphia	Brigantine
Long Beach Island	NJ	Philadelphia	Beach Haven, Long Beach, Ship Bottom, Surf City, Harvey Cedars, Barnegat Light
Barnegat Peninsula	NJ	Philadelphia	Island Beach State Park, Seaside Park, Seaside Heights, Lavallette, Mantoloking, Bay Head, Point Pleasant
Asbury Park & Manasquan	NJ	New York	Manasquan, Sea Girt, Spring Lake, Belmar, Avon-By-The-Sea, Bradly Beach, Asbury Park
Sea Bright	NJ	New York	Loch Arbour, Elberon, Long Branch, Monmouth Beach, Sea Bright, Sandy Hook

2.1.2 Mid-Atlantic Offshore Geology

In addition to beaches where sand is placed during nourishment, our study area also includes a 25-mile buffer onto the seafloor of the OCS. While historical beach nourishments have primarily utilized sand harvested within the 3-nautical mile limit separating state from federal waters, recent sand searches have begun to expand outward, beyond 10 miles offshore in some cases. Given the increasing variety of activities on the OCS and the potential for new developments in dredging and sand transport technologies over the 21^{st} century, we chose to include this wide stretch of seafloor in our modeling and analytical efforts. It should be noted, however, that geological and geophysical data become increasingly sparse with distance from shore, and this limits comprehensive assessments of spatial distributions of potential seafloor resources and habitat types.

Migrating sand ridges are a nearly ubiquitous feature of the U.S. Mid-Atlantic shelf, extending from around the Nantucket Shoals (off Massachusetts) to Cape Hatteras, North Carolina (Swift and Freeland 1978, Swift et al. 1978, Swift et al. 1979, Field 1980, Swift 1980, Swift and Field 1981, Rine et al. 1992, Conkwright and Gast 1995, Conkwright and Williams 1996, Goff et al. 1999, Conkwright et al. 2000, Hayes and Nairn, 2004, Snedden et al. 2011, Pendleton et al. 2017, Nicholson et al. 2019). Most shallow shelf areas (<150 feet in water depth) are characterized as sandy and have below 20 percent silt content (Shepard and Cohee 1936; Freeland and Swift 1978; Knebel 1981). Surficial sand and gravel deposits, the latter associated with erosional windows exposing basal lag deposits associated with Holocene marine transgression, drape a complex stratigraphic cut-and-fill architecture tied to Quaternary sea-level fluctuations with glacial advances and retreats (Foyle and Oertel 1992, Belknap et al. 1994, Foyle and Oertel 1997, Mallinson et al. 2005, Brothers et al. 2020, Mattheus et al. 2020b, Wehmiller et al. 2021). Buried shelf paleovalleys connect to paleochannels imaged beneath modern estuaries (e.g., Delaware Bay and Chesapeake Bay) and their respective bay-margin drainage networks (Knebel et al. 1988, Colman et al. 1990, Chen et al. 1995, Hobbs III 2004, Childers et al. 2019). The result of this geologic history is an array of sand deposits including large, well-defined shoals, relatively flat sheet sands, and complexes of finger shoals and muds across the region. Areas of highly heterogeneous seafloor composition are particularly challenging for sand resource assessments and dredging activities. Similarly, submerged fluvial, estuarine, and barrier deposits are rarely targeted for sand resource investigations due to spatial heterogeneity, potential cultural resource issues, and other logistical reasons.

2.2 Sand Demand Forecasting

2.2.1 Classifying Past Nourishments

Looking at historical beach nourishments allowed us to establish a baseline of sand usage for the study beaches. Some beaches referenced in this report may contain multiple municipalities or beach areas with different nourishment histories (Table 1). In these cases, total amounts of sand were aggregated for the whole beach. Sand placements for individual municipalities were more common in the 20th century, but more recent large-scale coastal management plans and beach nourishment projects by the US Army Corps of Engineers (USACE) tend to encompass entire shoreline units. Historical nourishment data was extracted from the American Shore and Beach Preservation Association's (ASBPA) beach nourishment database (Elko et al. 2021). Where possible, entries were validated by reviewing project specific documents.

Past beach nourishment projects were divided into three categories:

- Reconstruction: Projects where entire dune and beach structures are repaired or built from scratch. These projects occur rarely and utilize very large volumes of sand, often several times larger than a single periodic nourishment.
- Periodic Nourishments: Projects with pre-planned volumes of sand and placement intervals (e.g., 750,000 cubic yards (cy) every 4 years). These projects ideally follow a schedule established by local coastal engineering studies, often conducted by the USACE. Though smaller in terms of volume than Reconstruction events, the Periodic Nourishment category accounts for the majority of sand volume used in recent historical nourishments and forecasted sand demand.
- Emergency Repairs: Projects in response to a major erosion event or hot spot of erosion. Emergency Repairs are highly variable in the amount of volume used and timing. Many emergency repairs were small enough that they did not meaningfully contribute to total cumulative sand volumes used in recent beach nourishments.

Where possible, information on fill density (i.e., cy of sand applied per linear foot of beach) was collected for each of these categories, which allowed for gap filling of missing data and estimates of sand usage for hypothetical future nourishments and reconstructions.

2.2.2 Scenario-Based Forecasting

Though projections vary, it is well-established that the frequency and intensity of destructive coastal storm surges will increase throughout the 21st century in the Mid-Atlantic (Ezer and Atkinson 2014, Little et al. 2015, Vitousek et al. 2017, Vousdoukas et al. 2018, Lin et al. 2019, Pringle et al. 2021, Mayo and Lin 2022). These increases may be driven by mid-to-late-century RSLR (Vitousek et al. 2017, Tebaldi et al. 2021), long period tidal patterns (Rashid et al. 2021), changes in extratropical and tropical cyclone climatology and surge level (Lin et al. 2019, Marsooli et al. 2019), or, most likely, a combination of these factors (Little et al. 2015, Mayo and Lin 2022, Muis et al. 2023). Many of these forecasts incorporate the Representative Concentration Pathway 8.5 of the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5 RCP8.5), an estimate of future greenhouse gas concentrations that largely tracks with current trends and stated goals. However, climate ensemble projections suggest that even in climate scenarios with major reductions in greenhouse gas emissions (i.e., RCP2.6), coastal flood hazards will still increase substantially throughout the 21st century due to the continuation of RSLR (Little et al. 2015, Tebaldi et al. 2021).

In the previous study by Warner et al. (2023), emergency beach nourishments were added to forecasts if a randomly generated 100-year storm surge event were to occur within a given simulation year (i.e., at a baseline scenario, each year has a 1% chance of randomly having a major storm surge event). However, it is increasingly evident that major beach erosion events do not only correspond to single high magnitude storms; sequential smaller surge events can also cause large scale beach and dune erosion (Dominguez et al. 2024). Erosion is also affected by changing nearshore currents and prevailing wind directions. These smaller events (e.g., a 5- or 10-year storm surge) are forecasted to substantially increase in frequency over the next several decades, long before the end of the century, at which time they will likely be commonplace (Tebaldi et al. 2012, Marsooli et al. 2019, Tebaldi et al. 2021, Muis et al. 2023). We reviewed several studies with projections of increased storm surge and coastal flooding frequency specific to the Mid-Atlantic and used them to create a variety of potential scenarios for accelerating beach sand demand in our forecasts from 2025-2100. In this study, sand demand forecasts now incorporate both small storm surge events (major high tide flooding events likely to trigger an emergency nourishment) and major storm surge events (100+-year storm surges that may require a full coastal reconstruction).

It is important to recognize the key assumptions of these forecasts:

- Beach nourishment will remain the primary strategy for coastal stabilization. Under these forecasts, we assume that sea walls, breakwaters, or other hard structures will not be used in tandem with beach nourishment.

- There are no monetary or logistical constraints. Under these forecasts, we assume that there is adequate funding, dredge availability, and accessible sand to conduct beach nourishment.

These assumptions may be shocking to someone in the field of coastal sediment management. Individual beach nourishment projects have many components and hurdles, such as contracting dredging companies, environmental permitting, public engagement, and even physically locating suitable sand (Kolodin et al. 2021). We make these assumptions because the goal of this forecasting is to give a broad estimate of the volumes of sand and frequency of projects that would be needed to support beach nourishment operations as they are currently conducted into the future.

Similarly, estimating sand loss following an individual storm erosion event can be a highly technical and data-intensive exercise requiring information of beach profiles, maximum wave heights, and other simulation parameters (Lemke and Miller 2020, Simmons et al. 2019). While these simulations can be quite accurate at predicting beach erosion, they are not suitable for such a broad, long-term, and regional study as this. Our approach to estimating future beach sand demand instead relies on past trends of beach nourishment and projections of future storm event frequencies. Uncertainty is propagated using many bootstrapped simulations accounting for random variations in beach nourishment timing, volume, and storm severity under different hypothetical scenarios. A few beaches in this study lack detailed information on variations in nourishment size or volumes of sand used per linear foot of beach during nourishments versus major beach and dune reconstruction. In these cases, values were inferred from means and standard deviations of all beaches within the study region.

During each iteration of the forecast simulations, minor and major storm erosion events were randomly generated from 2025 to 2100 based on end-of-century forecasted occurrence probabilities of what are currently considered major high tide flooding events (minor erosion events) and 100+-year storm surges (major erosion events). Both events cannot occur in any single year of the forecast. Minor erosion event probabilities were based on 2050 frequency estimates of Sweet et al. (2022). Major erosion event probabilities were based on 2100 return periods of extreme sea levels estimated in Tebaldi et al. (2021), which bases estimates on the consensus of several earth system models under different warming and ice melt scenarios adapted from the approach of Rasmussen (2018), and Mayo and Lin (2022), which employs more localized coastal flooding analysis for specific tide gages along the Mid-Atlantic. In our forecasts, the probability of these events occurring increases linearly throughout the 75-year forecast period. In reality, such increases may be nonlinear due to changes in rates of RSLR, emissions reductions, or changes in coastal engineering practices. In conservative climate change projections, major high tide flooding frequency (e.g., a current 10-year event) are estimated to quadruple in the Mid-Atlantic by 2050 (Sweet et al. 2022) and be almost constant by 2100. Frequencies of high impact major (100+-year) surge events are expected to increase substantially by 2100, and, in the worst-case projections, such extreme surge events may occur once every 1-2 years in the study region (Tebaldi et al. 2021).

Identifying real life examples of major storm surge events corresponding to specific recurrence intervals (e.g., 100-year) can be difficult, as storm surge impacts vary spatially and depend on local tide conditions, coastal morphology, and variations within a storm system. Additionally, return intervals based on extreme value statistics have inherent uncertainty, as data are very sparse for extreme events. Hurricane Sandy (2012), for example, caused major coastal erosion and extensive damage to infrastructure in the Mid-Atlantic. Statistical estimates of its return interval range from less than 100 years to 1000 years depending on statistical methodologies and tide gauges considered (Lopeman et al. 2015, Suro et al. 2016). Nevertheless, the storm surges experienced across much of the study region during Hurricane Sandy would represent a "major erosion event" in the context of this study. For perspective, it is estimated that Hurricane Sandy caused a total beach sand loss of 2.2 million cubic yards (mcy) along the Asbury Park & Manasquan beach unit alone (USACE 2025).

Each iteration of the forecasts included random variations in the occurrence of erosion events under different scenario parameters as well as random variations in the volumes of sand used for nourishment and reconstruction events based on past observations. Thus, the forecasting scenarios produced a range of potential sand resource demand from which we could infer average forecast trends and uncertainties. Estimated sand volumes to address major storm surge erosion events were randomly selected from a uniform distribution spanning 50% to 100% of sand volumes used in past major beach reconstructions at each beach. For beaches where major reconstructions have not occurred, these numbers were estimated based on the regional averages of cy sand per linear foot of beach used in reconstructions. Estimated volumes of sand used in scheduled periodic nourishments and to address minor storm surge erosion events were randomly selected from a uniform distribution spanning the interquartile range (very few beaches had normal distributions of historical sand volume usage) of past nourishment events. Only one beach, Barnegat Peninsula, NJ, lacked a sufficient nourishment record to establish its interquartile range, and its interquartile range was instead estimated based on regional quartiles of cy sand per linear foot of beach used for historical periodic nourishments. This lack of historical nourishment data for Barnegat Peninsula should be noted as it did increase the uncertainty of sand demand forecasts for that beach. The logic behind including two levels of storm surge erosion severity was that rare, major erosion events would feature extensive washout of beach sand, dune breaching, and dune erosion, which would require volumes of sand that far exceed what would be needed to simply replenish sand on the beach face itself. The specific details of each forecast scenario are described below.

Scenario 1: Baseline

This scenario uses current USACE and historical design nourishment volumes and intervals. Major and minor storm surge events are assumed to maintain 100- and 10-year return periods through 2100 with no effects of RSLR or changing storm surge climatology.

Scenario 2: Low level increase erosion events

This scenario uses low end estimates of increased frequencies of 100- and 10-year return intervals at 2100 and 2050, respectively. A 100-year return interval of 22.2 years for Atlantic City, NJ was used from Mayo and Lin (2022) sea level rise-only scenario. A 10-year return interval of 4 years was taken from low end regional estimates of Sweet et al. (2022) for 2050.

Scenario 3: Medium-Low level increase in erosion events

This scenario uses medium-low end estimates of increased frequencies of 100- and 10-year return intervals at 2100 and 2050, respectively. A 100-year return interval of 11.4 years for Atlantic City, NJ was used from Mayo and Lin (2022) sea level rise plus changes in climatology scenario. A 10-year return interval of 2.5 years was taken from mid-range regional estimates of Sweet et al. (2022) for 2050.

Scenario 4: Medium level increase in erosion events

This scenario uses medium estimates of increased frequencies of 100- and 10-year return intervals at 2100 and 2050, respectively. A 100-year return interval of 3.1 years was used based on regional mean estimates of extreme maximum water levels at 1.5 degrees of warming by Tebaldi et al. (2021). A 10-year return interval of 2 years was taken from upper-range regional estimates of Sweet et al. (2022) for 2050.

Scenario 5: Medium-High level increase in erosion events

This scenario uses medium estimates of increased frequencies of 100- and 10-year return intervals at 2100 and 2050, respectively. A 100-year return interval of 2.1 years was used based on regional mean estimates of extreme maximum water levels at 3 degrees of warming by Tebaldi et al. (2021). A 10-year return interval of 1 per year was assumed by 2100.

Scenario 6: Highest level increase in erosion events

This scenario uses medium estimates of increased frequencies of 100- and 10-year return intervals at 2100 and 2050, respectively. A 100-year return interval of 1.5 years was used based on regional mean estimates of extreme maximum water levels at 5 degrees of warming by Tebaldi et al. (2021). A 10-year return interval of 1 per year was assumed by 2100.

It is important to note that the authors of this report do not endorse any particular projection of increasing coastal erosion risks over the 21st century. The inclusion of multiple projections is meant to highlight the uncertainty surrounding coastal erosion processes under rising sea levels and shifting climatology. This allows for estimates of offshore sand resource demand to reflect this uncertainty and aims to help coastal managers to prepare for best-to-worst case future scenarios.

2.2.3 Assessing Current Resource Availability

When possible, we estimated the potential lifespan of currently utilized borrow areas and shoals. However, such estimates are challenging if not impossible for dynamic, nearshore sand resources (e.g., inlets, harbors) that regenerate and/or migrate over time. It should be noted that estimates of borrow area lifespans have a substantial amount of uncertainty that will only grow as we look further into the future. In this report, we often use a conservative estimate that 50% of a sand resource's estimated volume will realistically be used, but, realistically, this percentage may be lower or higher. Sources of uncertainty include some mathematically quantifiable factors, such as calculation uncertainty from forecasts and volume estimates, as well as more unquantifiable factors, such as:

- Borrow area abandonment: a borrow area may be abandoned if it is found to have lower quality sand than initially suspected, is found to serve as an important habitat for marine life, is a cause of major pushback from the public, or is discovered to contain cultural resources or high risks from munitions of explosive concern/unexploded ordnance (MEC/UXO). If a nearby borrow area is abandoned, the demand for sand would then be compounded on any remaining resources in the area.

- Dredging practices: Patchwork dredging patterns make it more difficult for future dredging operations to locate quality sand within a borrow area, while repeated dredging can lead to "armoring" or coarsening of the seafloor sediments. Seafloor armoring refers to the accumulation of gravel or other coarse materials on the surface of a sand body due to screens being used on the dredge intake, which is necessary in areas of known MEC/UXO risks and thus widespread across the study region. In severe cases, this armored surface makes sand below inaccessible to the dredge.

- Nearshore processes: The fate of sand that is dredged offshore, placed on a beach, and eroded is poorly understood. If this sand accumulates in accessible nearshore areas (e.g., ebb shoals, sand bars, accreting beaches, etc.), it may potentially be recycled for future nourishments. This would reduce the demand for offshore borrow areas, potentially extending their lifespan. Encouragingly, sand backpassing from accreting to eroding areas of beaches has shown potential in some projects (e.g., Wallops Island, VA and Wildwood, NJ) rather than relying entirely on offshore sand sources. However, the nearshore environment is also ecologically and socially sensitive, as it may serve as popular fishing, swimming, and surfing areas. Even if eroded sand can be tracked to a specific sandbar or feature, public sentiment and/or ecological concerns may prevent it from being reused.

2.3 Modeling Offshore Sand Resource Quality

Efforts to model potential offshore sand resource quality in this study took place in two primary steps. First, offshore vibracore data were aggregated and quantified based on a unitless sand quality score. Next, potential sand resource quality was modeled across the OCS within our study area using spatial covariates derived from bathymetric data. This process is detailed in the upcoming sections.

2.3.1 Standardizing Offshore Lithological Data

Compared to the previous study by Warner et al. (2023), this expanded regional study incorporated a much larger set of offshore lithological data from vibracore sample records. These data were gathered as a long tabular dataset, largely based on qualitative, and primarily subjective, text descriptions of sediment characteristics in vertical layers. The sheer size of the dataset, as well as the differences in levels of detail and terminology in lithological descriptions, made it infeasible to manually interpret sand resource quality layer-by-layer. There was a clear need to standardize these core logs in a way that supported quantitative analysis. To achieve this, we employed techniques in natural language processing and neural network-based text classification to standardize and accelerate the analysis. These techniques allow standardized information to be extracted from complex strings of words.

2.3.1.1 Annotating Sand Resources Quality

First, a selection of lithology descriptions was examined from each source project (e.g., different vibracoring campaigns and different geologists), and each layer was given a score of sand resource quality from zero to five (Table 2). This provided a representative assemblage of abbreviations, shorthand, and styles of individual analysts. A score of zero would correspond to a unit of primarily clay, mud, silt, gravel, or some other combination of unusable materials, while a score of five would correspond to clean fine to coarse sand with at most a “trace” designation of shell or gravel. Criteria were based on conversations with coastal engineering experts to identify what characteristics in seafloor sediments are undesirable for beach communities or pose potential issues for dredging safety and efficiency. For example, abundant dense clays can cause issues for dredging heads. Conversely, modest amounts of silt may wash out, or gravel may be screened. Sand color was not considered in scores, as sand colors other than grey, dark grey, olive, brown, yellow, tan, and white were very uncommon in the dataset, generally only occurring in very thin layers.

In total, over 2000 lithological layer descriptions were manually annotated in this way. This provided a representative sample of description styles, classification schemes, and shorthand that could be fed into a machine learning model as a training dataset. Beyond sand resource quality, this approach may be applied as a means for extracting and predicting other variables of interest from large lithology datasets.

Table 2. Classification criteria for offshore lithological intervals

Criteria were based on conversations with coastal engineering experts to identify what characteristics in seafloor sediments are undesirable for beach communities or pose potential issues for dredging safety and efficiency.

Score	Criteria
0	Unacceptable. Any lithological unit where SAND is not the primary textural component
1	Poor. SAND is primary textural component, but abundant CLAY or ORGANIC components are noted
2	Low. SAND is primary textural component, but abundant SILT or GRAVEL components are noted
3	Moderate. Fine to coarse SAND is primary textural component, but some CLAY and/or SILT is noted
4	High. Fine to coarse SAND is primary textural component, with at most a trace of SILT and/or CLAY noted
5	Ideal. Fine to coarse SAND is primary textural component, with at most a trace GRAVEL and at most some shell fragments noted

Note: Terminology used in lithology descriptions is not always consistent across studies and projects. Some words like “trace” or “abundant” may correspond to actual grain size percentages in some descriptions, while serving as general descriptors in others. These criteria were established with the assumption that “trace” would mean a detectable but very small fraction of the sediment, while “abundant” would mean a fraction rivaling the primary textural component.

2.3.1.2 Preprocessing of Lithological Descriptions

Before the raw lithological descriptions could be used as a training dataset, they needed to be refined into a standard machine-readable format using tools from the field of natural language processing. First, all lithological descriptions were processed to remove nondescriptive words (e.g., “the”, “for”, “of”), and the remaining words were used to construct a unique word dictionary. This dictionary was reclassified into word roots to distill key sedimentological information from the qualitative text descriptions. For example, unique words of “silty” and “silt”, shorthand words of “slt” and “slty”, and common misspellings of “sitl” or “slit” were all reclassified to “silt”. After reclassification, only 42 unique descriptive words remained in the entire catalog of lithological descriptions.

Each word was then assigned to a unique integer, and lithological descriptions were converted from strings of words to strings of integers. These integer strings were padded with zero values such that all strings had an equal length, and the padded strings were ultimately fed into a convolutional neural network for sentence classification. Natural language processing was performed in the Natural Language Toolkit (nltk; Bird et al. 2009) package in Python (v3.12).

2.3.1.3 Convolutional Neural Network Training and Extrapolation

A one-dimensional convolutional neural network (CNN) was constructed and trained to predict sand resource quality classes based on the integer strings representing lithological descriptions. Model structures (e.g., number and size of convolutions, number and size of dense layers, normalization, dropout, etc.) were built based on previously published model structures and adjusted via trial-and-error to optimize model performance. For model development, the input dataset was split into 70% training, 20% testing, and 10% independent validation datasets. Once a suitable model structure was determined, hyperparameters were optimized using an iterative optimizer and internal cross-validation. All CNN modeling was performed using the packages keras (Chollet et al. 2015) and tensorflow (Abadi et al. 2015) in Python (v3.12). Model performance was evaluated based on the mean absolute error and ordinal prediction accuracy of training, testing, and validation datasets. The final model structure is illustrated in Figure 2.

First, standardized integer strings are fed through a positional encoding layer, which applies weights to the integer string based on the relative positions of the unique integers (i.e., words) to each other. This allows the model to learn based on sentence structure as opposed to just a simple collection of words. Next, the data are fed through a convolution layer that applies a series of filters and transformations to the data that enhance certain structures. The data are then passed through a series of fully connected layers (which learn the data structures) punctuated by dropout layers (which randomly remove connections to limit overfitting) before being flattened and fed into a final prediction layer. This process is iterated until testing set performance is maximized and before the model begins to overfit the data.

The final CNN had a validation set classification accuracy of 60% (i.e., classes were perfectly predicted), while over 94% of predictions were within 1 class of their target. This was deemed adequate for the next step, which was to extrapolate the CNN across all layers of our lithology dataset and aggregate the layers of each core into a score of sand resource quality over its entire length.

2.3.1.4 Overall Core Sand Resource Quality

Once the CNN was extrapolated, each layer of each core log was stacked to generate an aggregate "Sand Resource Quality" score over its upper 9 feet similar to the "stack-unit mapping" approach used by Ramsey and McKenna (2002). The limit of 9 feet was chosen based on feedback from experts in the field. Dredges tend to remove material in a series of 2- to 3-foot-deep passes, and they generally do not make more than 3 passes to avoid creating pits or "dead zones" on the seafloor, where oxygen may be depleted. The score of each core layer was multiplied by its thickness and added sequentially from top to bottom. If a core layer had a thickness greater than 0.5 feet and a quality score of 1 or less, the remaining lower portion of the core was given a score of 0. This is because if dredgers hit a sufficiently poor-quality layer in a sand deposit, the rest of the deposit will likely be abandoned. For this analysis, we assume that if a dense layer of clay and mud sits above high-quality sand deposit, that sand is still effectively unusable, as the dredge will not remove poor material just to access material below, regardless of its quality. However, there may be rare circumstances where there is a beneficial use of this overburden material (e.g., marsh restoration) that then allows access to the sand below.

This process was performed for all cores in the regional dataset, which were then used to develop spatial models of potential sand resource quality across the study region. The result was a sediment core dataset with a unitless value of sand resource quality ranging from 0 to 5, with 5 being the highest score. A score of 5 represents a clean fine- to coarse-grained surficial sand deposit, while a score of 0 would represent a core with abundant surficial mud, clay, gravel, or other unusable material.

Upon reviewing the extrapolated core sand resource quality scores. We found a clear bias in offshore core data that has emerged in the past 20 to 30 years. Recent (1990 or 2000 onward) offshore core surveys have overwhelmingly focused on beach quality sand resources, with poor representation of other sediment types. Figure 3 illustrates how the number of core samples that scored low (0-2 on our scale) has remained relatively static over the time intervals considered, while the number of core samples that scored high (4-5) now outnumber low scoring cores by 3 to 4 times (Figure 3). This bias is likely due to a difference in motivation behind sampling efforts. Historical offshore sampling focused on studying and mapping different OCS facies in a geological context, but focus has shifted towards identifying or confirming offshore sand resources since the widespread adoption of beach nourishment as a coastal stabilization strategy since the 1990s. While this may optimize costs for specific projects, it has led to an overrepresentation of certain seafloor features (e.g., sandy shoals) in recent core datasets. This issue is particularly problematic in offshore environments where sediments may shift over time, and the surficial sediment characteristics recorded in older geological surveys may no longer reflect the characteristics today. This may lead to reduced confidence in or loss of geologic information for non-shoal areas where recent surveys do not exist.

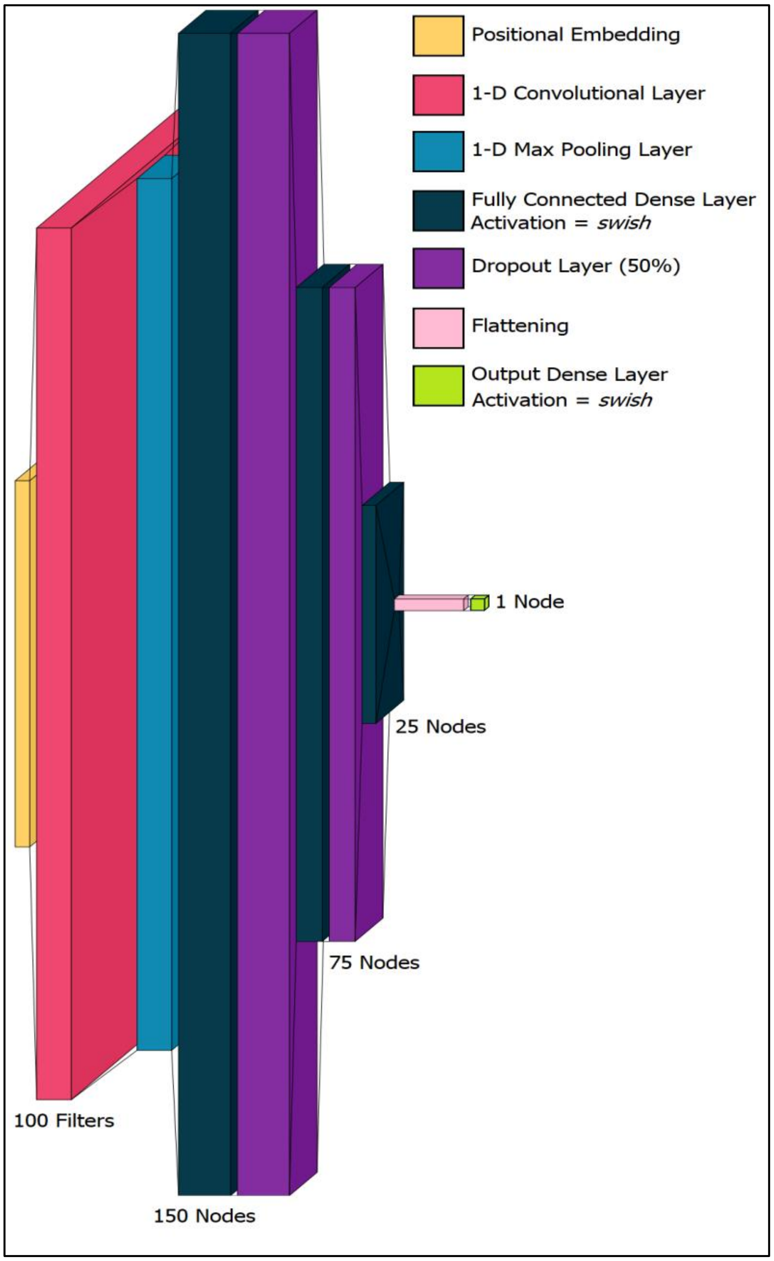

Figure 2. General structure of the convolutional neural network used for natural language processing in this study

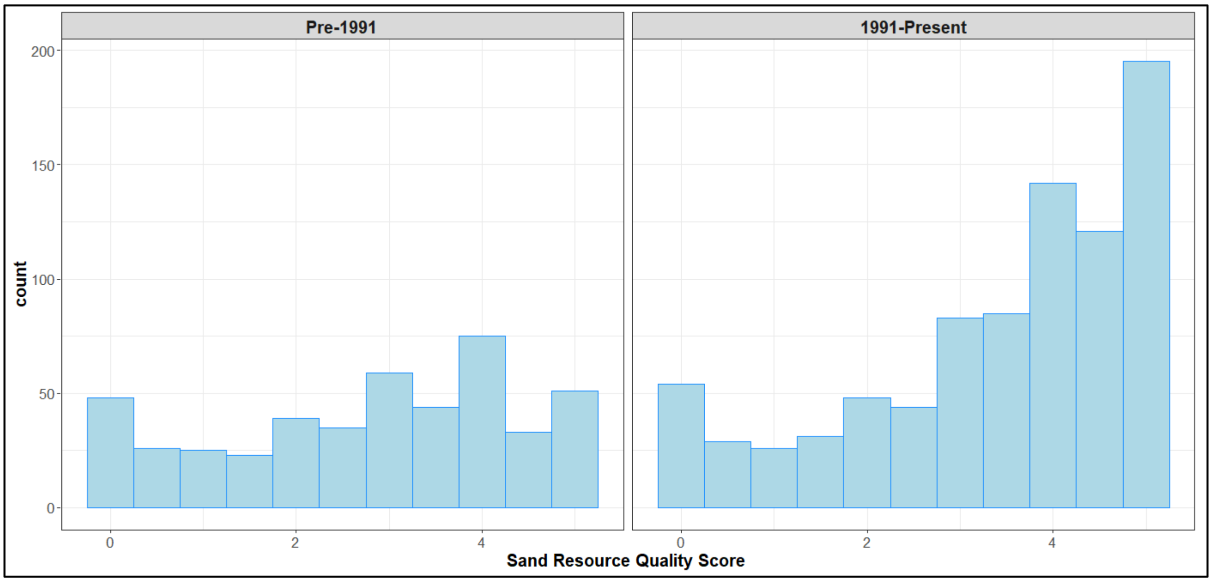

Figure 3. Histograms illustrating the bias towards high quality beach sand resources among offshore vibracore samples in the Mid-Atlantic
Although total core counts are much higher since the 1990s, the distribution of cores is heavily skewed towards high-quality sand resources.

2.3.2 Regional Geospatial Modeling of Potential Sand Resource Quality

After the standardization of the dataset of core sand resource quality, we developed a statistical model for predicting spatial patterns of sand resource quality across the a roughly 25-mile buffer from the coastline within the study area. This zone included both state waters and federal waters beyond the 3-nautical mile limit. The outputs of this model support long term offshore planning efforts by suggesting areas that may contain valuable sand resources, allowing managers to avoid potential resource conflicts and inaccessibility (e.g., a submerged data cable laid across an excellent sand resource area would make it inaccessible). This was accomplished by identifying relationships between the values of sand resource quality from the core dataset (i.e., point data) and local bathymetric derivatives (i.e., spatial covariates) in a similar approach to that of Warner et al. (2023).

2.3.2.1 Bathymetric Derivatives

Bathymetric derivative layers were prepared in the System for Automated Geospatial Analysis (SAGA) GIS software. The primary bathymetry source was from the National Oceanic and Atmospheric Administration’s (NOAA) 2023 Coastal Relief Model (CRM), which was assembled from a variety of bathymetric sources and resampled to a uniform resolution of one arc-second (NOAA 2023). This dataset was chosen because it is widely available and standardized across our regional study area. Bathymetry was masked to include only pixels on the continental shelf within 30 miles of shore. This dataset has numerous artifacts (e.g., striping, speckling) that are inconsistent spatially due to the patchwork nature of various data sources used to produce it. Several preprocessing steps were taken to reduce such artifacts, although they were not entirely eliminated. There was a necessary balance between removing artifacts and obscuring fine details of the seafloor surface. First, the masked coastal relief model was run through a Fast Fourier Transform filter to reduce striping, followed by a low-pass resampling filter with a 3-pixel radius to reduce speckling. This yielded a smoother bathymetric surface while still maintaining the major structural features of the seafloor, however some striping is still evident, particularly south of Long Island, NY and central New Jersey.

All subsequent bathymetric derivatives were generated from this processed surface and are presented in Table 3. We considered derivatives that performed well for seafloor classification in previous studies, including bathymetric position indices, seafloor curvature, and surface roughness (Koop et al. 2021, Pickens et al. 2021, Summers et al. 2021, Warner et al. 2023). Bathymetric derivatives were extracted for the pixels corresponding to each core location in the sediment core dataset.

2.3.2.2 Modeling Sand Resource Quality

Some preparation of the sediment core dataset was necessary prior to modeling. First, cores that were collected prior to 1995 were excluded, putting all cores used in modeling within ±15 years of when the bulk of the bathymetric data for the NOAA CRM were collected. This was done to reduce potential instances where major shifts in seafloor morphology may have happened between the time that a core was collected and when the bathymetric surface was generated. Cores shorter than 9 feet were also excluded to ensure that all cores were deep enough to capture multiple dredge passes (~2-3 feet) worth of material. Next, the strong bias towards high-quality beach sand resources in the training dataset needed to be addressed. This was accomplished by binning core data based on their sand resource quality scores and randomly sampling roughly even numbers of samples from each bin. This preprocessing resulted in the core dataset being reduced from 1301 entries to 307, but what remained were all relatively recent and evenly distributed sediment core samples suitable for further statistical modeling. Figure A-21 in Appendix A.2 illustrates the spatial distribution of these cores.

A final set of predictors was identified using a process of fitting simple, non-linear regression trees to the data and iteratively excluding predictors. Predictors with little predictive power or with strong correlations to other predictors were then excluded, resulting in a smaller set of strong predictors that avoided redundancy and potential multicollinearity issues. These predictors, in order of variable importance, were Convexity (Conv9; 9-pixel radius), Convexity (Conv27; 27-pixel radius), Terrain Ruggedness Index (TRI27), and Depth.

Table 3. Bathymetric derivatives and descriptions

These derivatives were used for modeling spatial distributions of potential sand resource quality on the OCS. Derivatives and evaluation radii that were selected for the final model are bolded.

Table Header (center)	Table Header (center)
Bathymetric Position Index	A measure of a pixel's position relative to its surroundings within a 3 and 9-pixel radius: $BPI = z - mean(z_n)$ Where z is the depth of the center pixel and $mean(z_n)$ is the mean depth around it within an n-pixel radius.
Convexity	The degree of convexity of the bathymetric surface evaluated in a **9 and 27-pixel radius.**
Depth	Depth from surface
Distance from Shore	Linear minimum distance from the shoreline
Eastness and Northness	The degree to which a bathymetric slope faces east or north.
Multiresolution Bathymetric Position Index	Similar to BPI, this is a composite measure of a pixel's position relative to its surroundings evaluated iteratively within an increasing 1 to 27-pixel radius. The advantage of this is that it can provide details on both coarse and fine topographic features.
Slope	The maximum downhill angle of a pixel on the bathymetric surface.
Terrain Ruggedness Index	A measure of 3-dimensional terrain ruggedness evaluated in a 9 and **27-pixel radius**.

This study used a non-linear Random Forests algorithm (RF) for fitting core sand quality scores to local bathymetric characteristics of each core location. RF is a commonly used classification and regression tree-based machine learning algorithm that is popular due to its ability to consider non-linear and multivariate relationships within a dataset while remaining relatively computationally efficient (Breiman 2001). Briefly, it creates a large ensemble of weak regression trees (a forest) based on random subsets of data and predictor variables. Then final predictions are made based on the consensus across all trees. This helps reduce model overfitting and overemphasis on any particular predictor variable.

First, the input dataset was randomly split into a 70% training dataset and a 30% independent testing dataset. Next, the training dataset was subjected to a 5-fold cross validation process for optimizing model hyperparameters using the "ranger" and "caret" packages in R statistical software (Wright and Ziegler 2017, Kuhn 2008, R Core Team 2024). Tuned parameters included mtry (the number of variables considered at each node in the decision trees), minimum node size (the minimum number of samples needed in each terminal node), and ntree (the number of decision trees grown in the model). The best performing model that minimized root mean square error (RMSE) across cross validation splits had a mtry of 1, minimum node size of 6, and ntree of 500. These parameters were used for training the final RF model and evaluating it using the testing set data.

The final RF model had a testing set R^2, mean absolute error (MAE), and RMSE of 0.59, 0.98, and 1.17, respectively (Figure 4a). Though this indicates robust predictive performance, our model predictions exhibited an averaging bias, where predictions underestimate observations at the high end and overestimate observations at the low end (Figure 4). This is a common occurrence with many machine learning algorithms, and several postprocessing methods have been proposed to scale machine learning predicted values to the full ranges of the observed dataset (Belitz and Stackelberg 2021). We employed a simple Linear Transform Function that helped map random forests predictions to the true ranges of the training dataset. This does not affect the R^2 value of the model, as it does not affect the relative distribution of model predictions, but it does improve the MAE and RMSE, in this case reducing testing set MAE and RMSE to 0.87 and 1.08, respectively (Figure 4b).

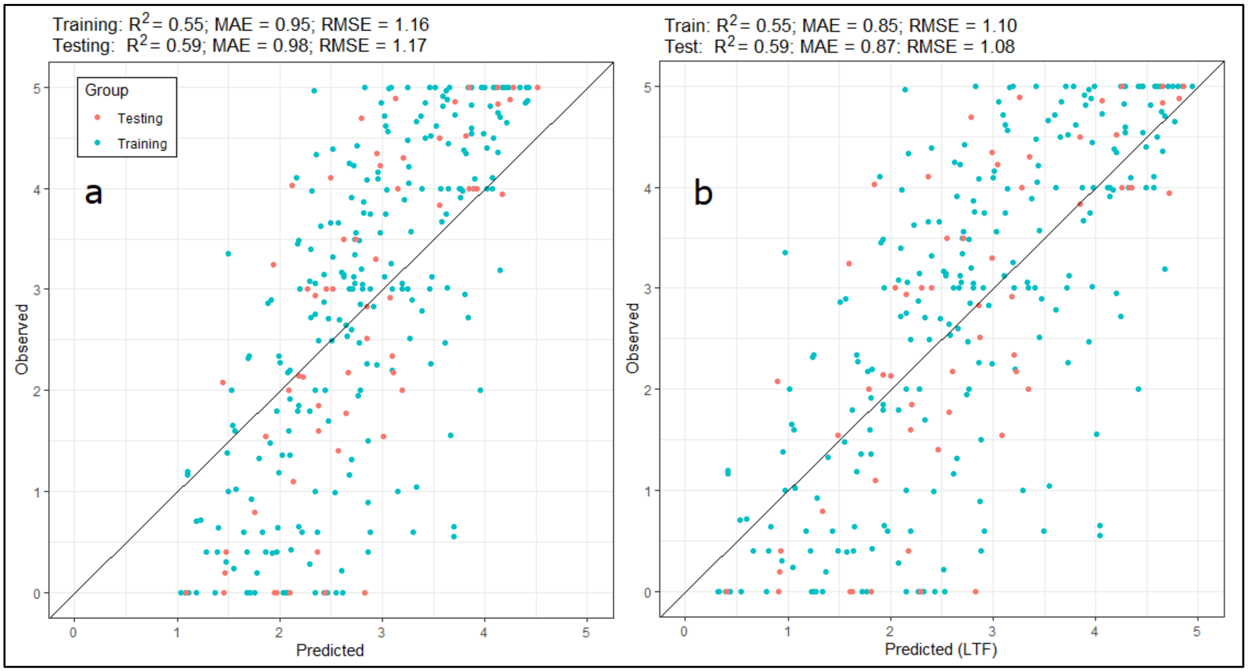

Figure 4. Model predictions versus observations

Comparison of core sand resource quality predictions from the Random Forests model before (a) and after (b) the application of a Linear Transform Function to better scale model outputs. Model performance metrics are noted above each plot.

This final model was then extrapolated across the raster layers of the four predictor bathymetric derivatives, generating a map of spatial patterns of potential sand resource quality on a scale of 0 to 5 (Figure 5a). To make the model output more useful for offshore planning purposes, it was subjected to a 5-class Object Based Image Segmentation algorithm in SAGA GIS. This yielded a categorized map of predicted sand resource quality levels across the OCS in our study region that is more interpretable than the raw model output (Figure 5b).

Two important things should be noted about these model predictions:

1. Most of the training data comes from within 5 miles from shore, and only rarely extends beyond 10 miles. This means that there is much less confidence in predictions of sand resource quality in the further offshore areas. Empirical data is scarce there, though anecdotal evidence from local fishing communities suggests that sandy seabed features extend far offshore.

2. Similarly, no training data came from within Chesapeake, Delaware, or Raritan Bays. For this reason, we masked out all bays from the final map, as they have very different sediment dynamics than the OCS and could lead to false assumptions about modeled sand quality.

Additionally, although the bathymetric dataset was preprocessed to reduce the occurrence of linear artifacts, some did remain. These artifacts were propagated into the bathymetric derivatives and ultimately the final model predictions. The result is some linear distortions visible in the segmented sand resource quality groups in certain areas, with particularly evident linear artifacts off central New Jersey (Figures 10, 11).

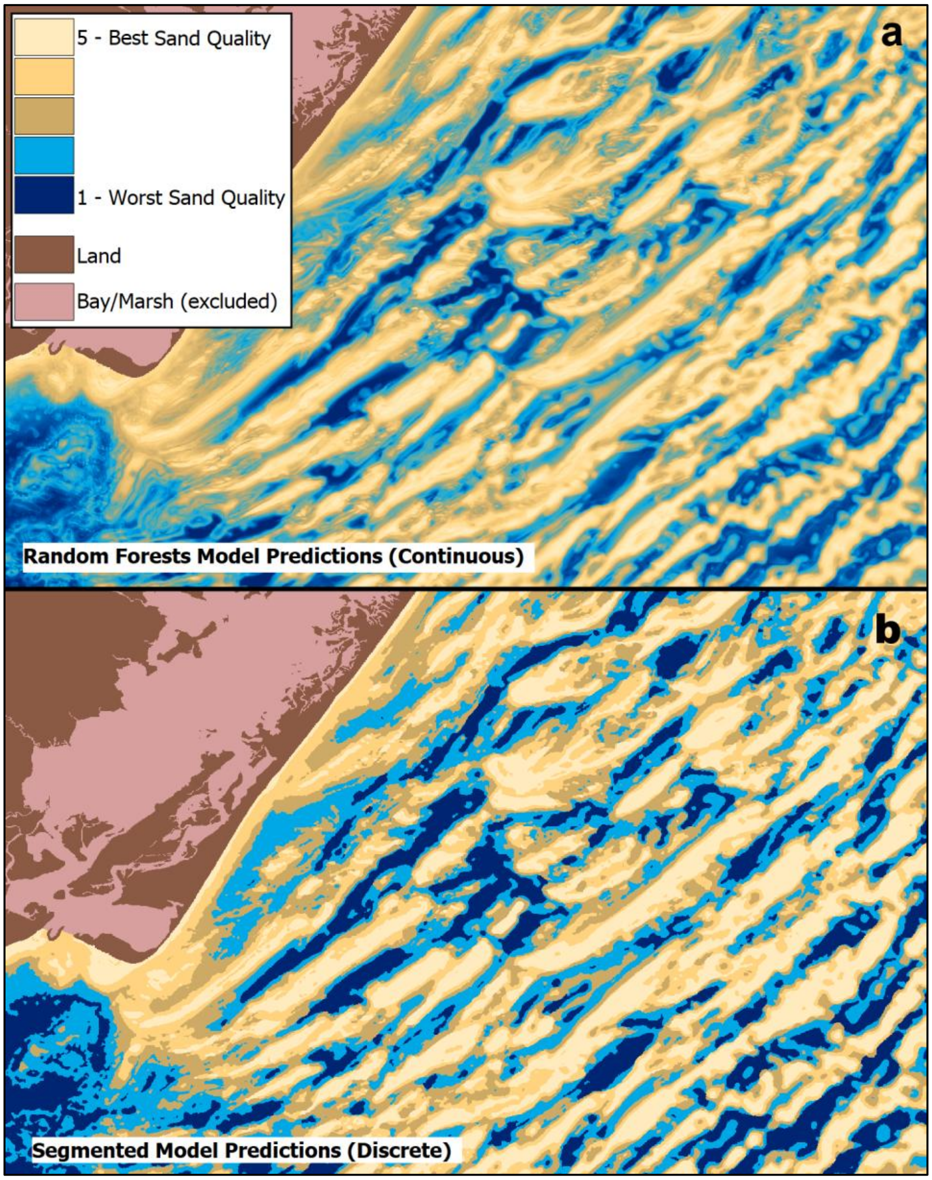

Figure 5. Example of Random Forests model predictions and segmented output
Raw predictions are continuous (a), and classified sand resource quality levels after image segmentation are discrete (b). The segmented output provides discrete units to better support offshore planning efforts.

3 Results and Discussion

3.1 Sand Usage History and Forecasts

In this section, we present a state-by-state overview of past and forecasted sand resource demand since 1990. We also discuss current borrow area availability and potential longevity, and we introduce estimates potential sand volumes proximal to each study beach.

3.1.1 Virginia

3.1.1.1 Virginia: Historical Sand Usage

The Virginia beaches in our study area are Sandbridge, Virginia Beach, Dam Neck, and Wallops Island. Sandbridge is a primarily residential area south of Virginia Beach, which is highly developed and supports a major tourism economy. Both Sandbridge and Virginia Beach have received periodic beach major nourishments since the 1990s, with Virginia Beach undergoing a large reconstruction of 4.2 mcy in 2002. The two are separated by Dam Neck, which houses a naval air base and has received infrequent, but large, beach nourishments since the 1990s. To the north side of the Chesapeake Bay mouth is Wallops Island, which houses a National Aeronautics and Space Administration (NASA) space launch facility. Wallops Island has experienced significant erosion in the south and central portion of the island while also experiencing sand accretion on its north end. This has led to some backpassing of sand from north to south to help reduce demand for offshore resources. There are many barrier islands along the Virginia coast south of Wallops Island, but they are uninhabited and allowed to migrate and erode naturally. All Virginia beaches fall within the Norfolk USACE district.

Due to the rich military history of Virginia's Atlantic coastline, all nourished beaches in Virginia contain extensive offshore zones noted for potential MEC/UXO. While screening practices on dredges can reduce risks, areas where such dangers are abundant may be removed from consideration as potential sand resources. Additionally, screening for MEC/UXO can create sand armoring issues, which may reduce the effective volume of sand available in a resource.

3.1.1.2 Virginia: Past and Current Sand Resources

Virginia's Atlantic beaches south of the Chesapeake Bay mouth have utilized a variety of sand resources over the past decades (Table 4). A substantial portion of historical beach sand for Virginia Beach has come from dredging of the nearby Rudee Inlet and the Thimble Shoal and Atlantic Ocean Channels at the mouth of the Chesapeake, including the major reconstruction in 2002. Dam Neck and Sandbridge both utilize sand from large offshore borrow areas (Sandbridge Borrow Areas A and B, Figure 6), which lie in federal waters and have an estimated remaining combined volume of roughly 27 mcy (Schnabel Engineering 2018).

The Wallops Island NASA facility protects its infrastructure through a combination of beach nourishment and recessed breakwaters in some areas. Wallops Island has employed both sand backpassing, where sand is moved from the accreting north end of the beach to the eroding central and south beach areas, as well as dredging from one of two large offshore shoals in federal waters (Unnamed Shoal A). This sand source has an estimated remaining volume of 63 mcy based on initial estimated volume (King Jr. et al. 2011) and volume removed.

Table 4. Past sand usage for the Atlantic beaches of Virginia (USACE Norfolk District) from 1990 to 2024

Beach	Sand Usage 1990 – 2024 (mcy)	Source Names
Dam Neck	2.1	Sandbridge Shoals A and B
Sandbridge	9.1	Sandbridge Shoals A and B
Virginia Beach	12.2	Rudee Inlet, Thimble Shoal Channel
Wallops Island	5.2	Unnamed Shoal A, North Wallops Island Beach

3.1.1.3 Virginia: Forecasted Sand Demands and Potential Resources

Table 5. Forecasted additional sand demands for the Atlantic beaches of Virginia
Forecasts span from 2024 to 2050 and 2100. Estimated demand represents the mean of bootstrapped forecast predictions, followed by the quartiles of bootstrapped forecast predictions in parentheses. For simplicity, we only present data from Scenarios 1, 4, and 6 to indicate baseline, medium, and maximum forecast ranges.

Beach	Scenario	Estimated Demand 2050 (mcy)	Estimated Demand 2100 (mcy)
Dam Neck	S1	8 (7-8.5)	22.1 (19.9-23.5)
Dam Neck	S4	12.3 (9.7-14.4)	56.5 (50.4-62.2)
Dam Neck	S6	17.2 (13.9-20.3)	98.1 (90.5-105.6)
Sandbridge	S1	20 (18.8-21.2)	55.5 (53.3-57.4)
Sandbridge	S4	23.5 (21.1-25.4)	84 (79-89.1)
Sandbridge	S6	27.7 (24.8-30.5)	125.2 (118.6-131.7)
Virginia Beach	S1	4.2 (2.9-5.2)	11.3 (8.8-13.5)
Virginia Beach	S4	9 (6.1-11.2)	48.9 (42.4-55.1)
Virginia Beach	S6	14.2 (10.7-17.6)	92.6 (84.4-100.2)
Wallops Island	S1	7.3 (6-8)	20.4 (18.2-22)
Wallops Island	S4	11.8 (9.1-13.9)	56.1 (49.8-62.1)
Wallops Island	S6	16.9 (13.8-19.9)	100.1 (92.9-107.4)
Total	S1	39.5 (34.7-42.9)	109.3 (100.2-116.4)
Total	S4	56.6 (46-64.9)	245.5 (221.6-268.5)
Total	S6	76 (63.2-88.3)	416 (386.4-444.9)

Forecasted sand demand for Virginia is highest for Sandbridge, likely due to its relatively long length and high historic sand usage. While Wallops Island is not surrounded by heavy development, the lower three beaches in Virginia are densely clustered. This may create high local demand pressure for sand resources in the future.

Below is an assessment of Virginia's current borrow areas (south to north):

- **Virginia Sandbridge Shoals A and B:** These borrow areas lay in federal waters and are the current sand supplies for Sandbridge and Dam Neck, VA. Combined, these shoals are estimated to contain a remaining 27 mcy of an initial estimated 29 mcy (Schnabel Engineering 2018), with most historical sand dredging confined to Shoal B. However, volume estimates from past site assessments have varied substantially. These resources are used both by the Sandbridge community and the US Navy. Based on our forecasts and a 50% sand extraction efficiency, we estimate that these borrow areas will continue to meet demand for Sandbridge and Dam Neck until 2040 to 2050 depending on the scenario. However, we note that there is uncertainty surrounding estimates of usable material volume and that MEC/UXO concerns may also reduce the effective lifespan of this resource.
- **Rudee Inlet:** Rudee Inlet sits just south of Virginia Beach and experiences significant shoaling, requiring frequent dredging to support boat navigation. This sand resource has been used for many small-scale nourishment projects for Virginia Beach over the past decades, and it will likely continue to do so. While this sand resource will not meet demand for major beach reconstruction or nourishment projects, it is anticipated to reduce some demand pressure on other area resources.
- **Thimble Shoals and Atlantic Ocean Channel:** Thimble Shoals and the Atlantic Ocean Channel are located at the mouth of Chesapeake Bay. These borrow areas have provided large quantities of sand for coastal stabilization projects for Virginia Beach and the US Navy, with Thimble Shoals providing an estimated 4.2 mcy for a major beach reconstruction in Virginia Beach in 2002 and several more mcy since then. Current estimates suggest 1.8 mcy and 13.3 mcy of usable sand remain in Thimble Shoals and the Atlantic Ocean Channel, respectively (Schnabel Engineering 2019). These resources sit in a dynamic seafloor environment due to the currents of the bay mouth, and this area requires maintenance dredging to maintain major shipping channels. However, their regeneration potential is not well understood, and concerns about sand quality and MEC/UXO hazards may limit their future use for beach nourishment. It is unclear how long these sand resources will be able to meet demand over the coming decades. Our forecasts of sand demand in Virginia Beach vary substantially across the different scenarios, which further complicate estimates of borrow area longevity. Investigations into alternative borrow areas for Virgina Beach are ongoing.
- **Virginia Unnamed Shoal A:** This resource was used for a major reconstruction project to protect the NASA Wallops Island Flight Center, and it contains an estimated remaining 63 mcy of an initial estimated 68 mcy (King Jr. et al. 2011). Extractable volume limits are placed on this shoal to preserve its morphologic integrity, which can be re-evaluated after dredging activities. This makes estimating the lifespan of the sand resource difficult. If only 10% of the initial estimated shoal volume (6.8 mcy), this sand resource will only meet demand for one to two more nourishment cycles. Conversely, 50% of the estimated initial volume of this shoal could sustain demand for the facility until at least 2060 (S6) and at most 2100 (S1 and S2). The lifespan of this resource may be further extended by backpassing efforts from North Wallops Island beach.
- **North Wallops Island Beach:** The north side of Wallops Island experiences significant sand accretion, similar to what is observed at Tom's Cove across Chincoteague Inlet. The facility has begun a sand backpassing program that moves accreted material down the island into areas that experience erosion. Estimated accretion rates of approximately 40,000 cy per year (King Jr. et al. 2011) make this program a low-cost option for small-scale nourishments targeting hotspot erosion.

Table 6 presents estimated sand deposits within a 10-mile buffer of Viginia's beaches based on classes 5 and 4 (best and second best) from our random forests model of sand resource potential. It is important to note that this is a modeled product and has a substantial amount of associated uncertainty. Additionally, these model estimates do not account for usage conflicts (e.g., fish habitat, already depleted sand units, cultural resources, offshore lease areas) or logistical challenges (e.g., shipping lanes, submerged cables, MEC/UXO). Volumes were conservatively estimated as a uniform thickness of 9 feet for Class 5 sand resource areas and 5 feet for Class 4 sand resource areas.

Table 6. Estimated acreage and volumes of sand deposits within a 10- mile buffer of Virginia beaches

Sand estimates are based off of total areas of classes 5 and 4 (best and second best) from the sand resource potential model developed in this study. As the potential sand resource quality score reflects both the character and thickness of the resource, volumes were conservatively estimated based on a uniform thickness of 9 feet for class 5 and 5 feet for class 4. Importantly, these are raw model estimates that do not reflect limitations from areas that have been designated as off-limits, areas with MEC/UXO risks, or resources that have been depleted since the collection of bathymetry. Buffers may overlap for adjacent beaches, in which case a sand resource volume is counted for both beaches.

Beach	Class 5 Volume Within 10 miles of Beach Centroid (mcy);(acres)	Class 4 Volume Within 10 miles of Beach Centroid (mcy);(acres)
Sandbridge	39;2695	71;8813
Dam Neck	107;7367	76;9416
Virginia Beach	190;13078	114;14168
Wallops Island	59;4094	73;9025

The model predicted relatively scarce sand resources near Sandbridge compared to Dam Neck and Virginia Beach. Notably, the model predicted heterogeneous beach sand quality in both Sandbridge borrow areas, which reflects the findings of substantial variability in surficial sand thickness from Schnabel Engineering (2018). Model predictions suggested slightly lower beach sand resource quality in Sandbridge Borrow Area A than B. The high predicted abundance of sand resources near Dam Neck and Virginia Beach is mainly due to a very large shoal that sits just south of the Atlantic Channel at the mouth of Chesapeake Bay (Figure 6). This resource intersects with a zone of suspected MEC/UXO hazards, but it could be a promising source of sand if adequate screening procedures are implemented. Wallops Island has a relatively large area of predicted poor sand resource quality to the south, but there are several large shoals offshore to the north. Model predictions align well with known beach quality sandy shoals (Unnamed Shoals A and B and Blackfish Bank; King Jr. et al. 2011). Wallops Island is flanked by uninhabited barrier islands, and competition for sand resources is unlikely. Like many other areas along the Mid-Atlantic coast, much of the seafloor surrounding Wallops Island is noted for MEC/UXO concerns.

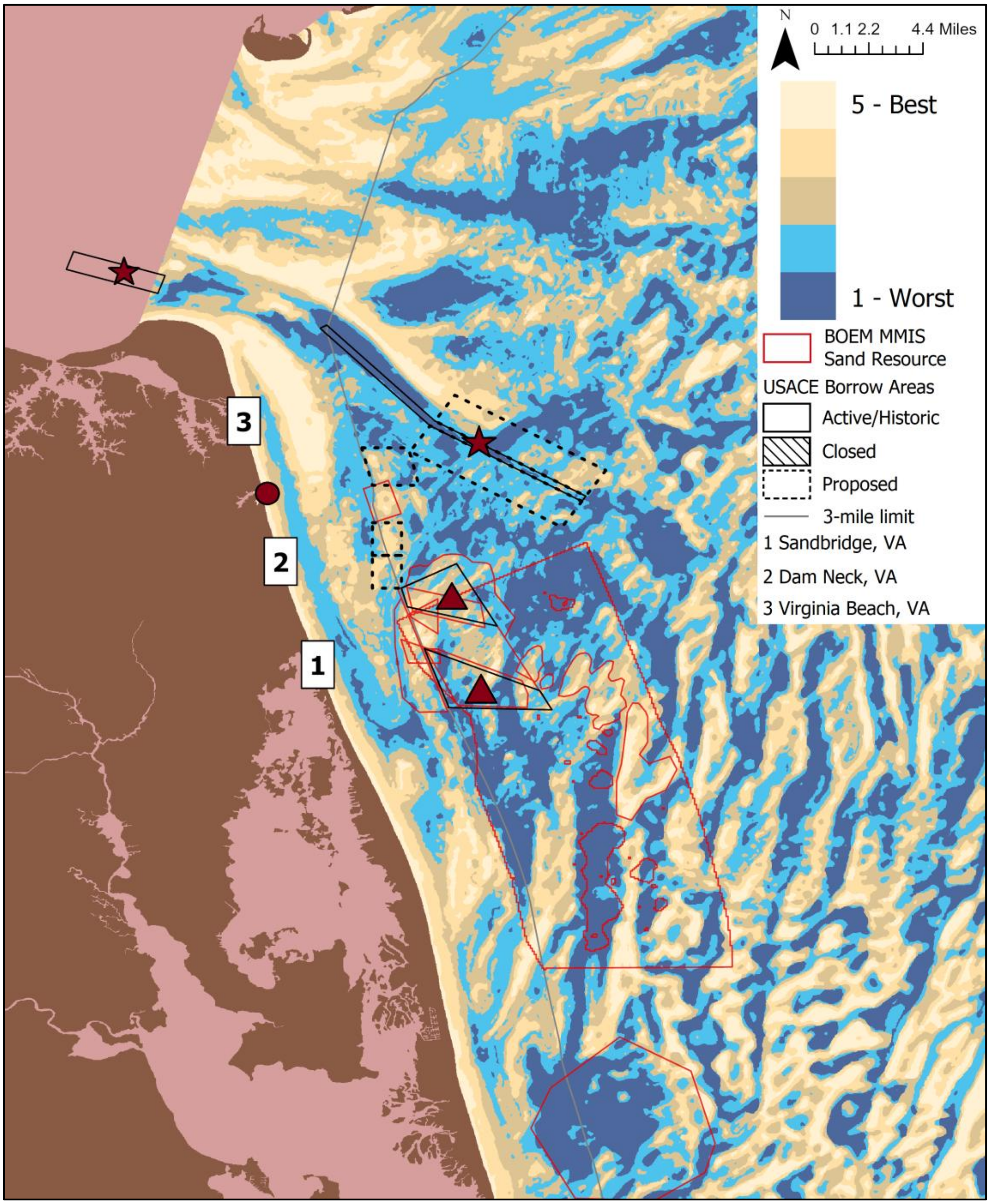

Figure 6. Modeled offshore sand resource potential for southern Virginia
Light tans indicate high predicted quality resources, while blues indicate poor predicted quality. Land and bays are displayed in dark brown and pink, respectively. USACE borrow areas (black solid, hashed, and dashed polygons) are noted with their current status of active/historical (i.e., currently utilized or confirmed and potentially available as future sources), closed (unavailable for future use), or proposed (potential resources that have not yet been approved). Sand resource areas from the BOEM Marine Minerals Information System (red polygons) are also noted, representing areas that have been identified by previous investigations as potential sand resources.Shapes indicate borrow areas discussed in text: Sandbridge Shoals A (bottom triangle) and B (top triangle), Rudee Inlet (circle), and Thimble Shoals (western star) and the Atlantic Ocean Channel (eastern star).

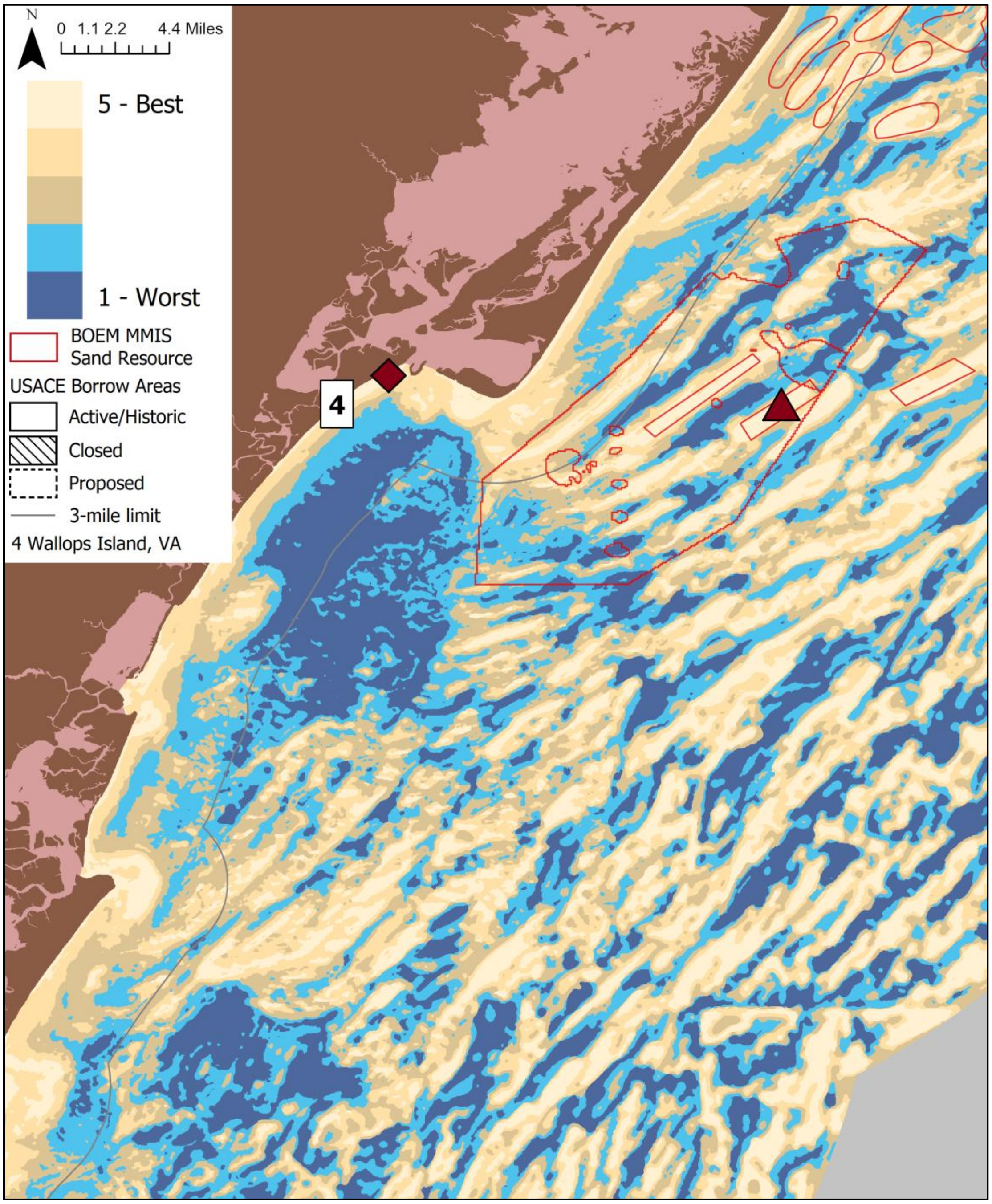

Figure 7. Modeled offshore sand resource potential for Wallops Island Flight Facility in Virginia
Light tans indicate high predicted quality resources, while blues indicate poor predicted quality. Land and bays are displayed in dark brown and pink, respectively. USACE borrow areas (black solid, hashed, and dashed polygons) are noted with their current status of active/historical (i.e., currently utilized or confirmed and potentially available as future sources), closed (unavailable for future use), or proposed (potential resources that have not yet been approved). Sand resource areas from the BOEM Marine Minerals Information System (red polygons) are also noted, representing areas that have been identified by previous investigations as potential sand resources. Shapes indicate borrow areas discussed in text: North Wallops Island Beach (diamond), which has substantial sand accretion like the nearby Tom's Cove, and Unnamed Shoal A (triangle).

3.1.2 Maryland

3.1.2.1 Maryland: Historical Sand Usage

The Maryland beaches in our study area are Assateague Island and Ocean City, MD. Assateague Island is a long barrier island extending south across the Virginia border that houses Assateague Island National Seashore (AINS) and Assateague State Park. AINS received a major beach nourishment in 2002 to repair a barrier island breach but has otherwise been allowed to evolve naturally. The state park receives frequent small nourishments from dredging of Ocean City inlet. Projections of sand demand for Assateague Island depend heavily on management decisions of AINS, and our forecasts operate under the assumption that it will be nourished at its current low level with periodic major repairs in response to major erosion events. It is evident from aerial photos that sand has rapidly accreted at the south end of Assateague Island in Tom's Cove, Virginia over the past several decades, likely due to longshore transport of eroded sand from AINS (Shawler et al. 2021).

Ocean City, MD supports a major beach tourism economy and has been heavily nourished over the last three decades. It is the only highly developed Atlantic beach to fall within the Baltimore USACE district. Ocean City is currently under a USACE coastal protection plan and had a major beach and dune reconstruction of 1.3 mcy in 1998 and large periodic nourishments since.

3.1.2.2 Maryland: Past and Current Sand Resources

Assateague Island received a major beach nourishment in 2002 to repair breaches in the island. This sand came from the offshore Great Gull Bank, which lies in federal waters. No additional offshore sand has been used for Assateague Island since. Rather, periodic nourishments of inlet dredging sand have been routinely placed at Assateague State Park to maintain its beach, with eroded sand being transported southward down the length of the island. If major barrier breaches occur on the island in the future, additional offshore sand may or may not be used for repairs, which makes demand forecasts uncertain.

While some of Ocean City's sand demands are also met by inlet dredging, additional offshore sand resources are also necessary to meet demand. Nearby sand resources in state waters have been largely exhausted or abandoned due to habitat concerns. Since 2021, Ocean City, MD has utilized sand from the Weaver Shoal, which lies in federal waters. This shoal is very large (~93 mcy; Conkwright and Gast 1994); however, dredging is limited to a maximum of 5% of initial estimated volume to protect shoal habitat. Under this constraint, Weaver Shoal may be removed as a sand source in the near future. Isle of Wight shoal (~136 mcy; Conkwright and Gast 1994), just south of Weaver Shoal, is likely the next offshore sand resource for Ocean City, MD.

Table 7. Past sand usage for the Atlantic beaches of Maryland (USACE Baltimore District) from 1990 to 2024.

Beach	Sand Usage 1990 – 2024 (mcy)	Source Names
Assateague Island	2.1	Great Gull Bank, Ocean City Inlet
Ocean City, MD	8.7	Weaver Shoal, Ocean City Inlet, MD Borrow Areas 2, 3, and 9

3.1.2.3 Maryland: Forecasted Sand Demands and Potential Resources

Table 8. Forecasted additional sand demands for the Atlantic beaches of Maryland

Forecasts span from 2024 to 2050 and 2100. Estimated demand represents the mean of bootstrapped forecast predictions, followed by the quartiles of bootstrapped forecast predictions in parentheses. For simplicity, we only present data from Scenarios 1, 4, and 6 to indicate baseline, medium, and maximum forecast ranges.

Beach	Scenario	Estimated Demand 2050 (mcy)	Estimated Demand 2100 (mcy)
Assateague	S1	2.7 (1.8-2)	7.7 (5.3-9)
Assateague	S4	7.1 (4.5-9.4)	44.1 (37.5-50.2)
Assateague	S6	12.1 (8.4-15.4)	85.4 (76.9-94)
Ocean City (MD)	S1	9.5 (8.4-10.5)	26 (24-27.5)
Ocean City (MD)	S4	13.9 (11.3-16.1)	60.3 (54.4-66.1)
Ocean City (MD)	S6	18.8 (15.5-22.1)	103.6 (96.5-110.6)
Total	S1	12.2 (10.2-12.5)	33.7 (29.3-36.5)
Total	S4	21 (15.8-25.5)	104.4 (91.9-116.3)
Total	S6	30.9 (23.9-37.5)	189 (173.4-204.6)

Maryland's current sand demand is almost entirely driven by Ocean City, MD. As noted, it is uncertain if beach nourishment or emergency repairs will be done on Assateague Island in the future, and future sand demand may be much smaller than suggested by our forecasts (Table 8). While existing borrow areas for Ocean City, MD may only sustain demand for one to two more decades, our modeling and historical survey data suggest abundant sand resources in shoal fields south of the city. Borrow areas and modeled sand resource quality are displayed in Figure 8. The seafloor near Maryland's beaches contains many large and well-defined shoals that are largely free of known MEC/UXO concerns. A number of these shoals, especially those within state waters, are off-limits due to habitat concerns. However, there are several other large shoals near the currently utilized Weaver and (likely) Isle of Wight shoals. While Ocean City, MD may face resource competition with Delaware's beaches to the north, resource competition to the south with the undeveloped Assateague Island is unlikely.

Below is an assessment of Maryland's current borrow areas (south to north):

- **Ocean City Inlet:** Ocean City Inlet is frequently dredged for navigation purposes and to supply sand for small local nourishment projects. The material from this inlet is primarily placed on the beach of Assateague Island State Park, but it has been used for other projects in the past. Based on its dredging history, we estimate that the sand deposits surrounding the inlet regenerate between 20,000 and 60,000 cy per year based on past dredging activities.
- **Weaver Shoal:** This large, offshore shoal has provided roughly 1.2 mcy for Ocean City, MD beach nourishment projects over the past 5 years. The original estimated volume of Weaver Shoal is 93 mcy, but dredging was limited to 5% of this volume. This limitation means that additional sand resources will soon be necessary to meet Ocean City's sand demands.

- **Isle of Wight Shoal:** This sand resource is the likely alternative to meet Ocean City, MD's sand demands in the near future, with an estimated volume of 136 mcy. If similar dredging limitations are placed on this sand resource (5% reducing usable volume to 6.8 mcy), Isle of Wight shoal borrow areas could meet demand for Ocean City, MD through 2040 to 2050.

Table 9 presents estimated sand deposits within a 10-mile buffer of Maryland's beaches based on classes 5 and 4 (best and second best) from our random forests model of sand resource potential. It is important to note that this is a modeled product and has a substantial amount of associated uncertainty. Additionally, these model estimates do not account for usage conflicts (e.g., fish habitat, already depleted sand units, cultural resources, offshore lease areas) or logistical challenges (e.g., shipping lanes, submerged cables, MEC/UXO). Volumes were conservatively estimated as a uniform thickness of 9 feet for Class 5 sand resource areas and 5 feet for Class 4 sand resource areas.

Table 9. Estimated acreage and volumes of sand deposits within a 10- mile buffer of Maryland beaches

Sand estimates are based off of total areas of classes 5 and 4 (best and second best) from the sand resource potential model developed in this study. As the potential sand resource quality score reflects both the character and thickness of the resource, volumes were conservatively estimated based on a uniform thickness of 9 feet for class 5 and 5 feet for class 4. Importantly, these are raw model estimates that do not reflect limitations from areas that have been designated as off-limits, areas with MEC/UXO risks, or resources that have been depleted since the collection of bathymetry. Buffers may overlap for adjacent beaches, in which case a sand resource volume is counted for both beaches.

Beach	Class 5 Volume Within 10 miles of Beach Centroid (mcy);(acres)	Class 4 Volume Within 10 miles of Beach Centroid (mcy);(acres)
Assateague	158;10863	84;10474
Ocean City	208;14297	114;14123

The model predicted abundant high quality offshore sand resources for beach nourishment distributed among large shoal features, which is consistent with the well-known sand ridges and shoal fields in this region. The structures and formational environment of these features are described in detail by Pendleton et al. (2017) and others before. Though these features likely contain very large volumes of beach quality sand, their distance from Ocean City and other coastal infrastructure makes most of them unlikely candidates as beach nourishment sand resources.

3.1.3 Delaware

3.1.3.1 Delaware: Historical Sand Usage

Delaware's Atlantic coastline is home to three major developed beach communities: Fenwick Island, Bethany/South Bethany Beach, and Rehoboth/Dewey Beach. All communities feature a mix of residential and commercial development with a strong beach economy. Each beach underwent a major beach and dune reconstruction in the early 2000s and have received periodic nourishments according to USACE coastal protection plans since. Delaware is also home to two long stretches of beach state parks (Fenwick Island S.P. and Delaware Seashore S.P.) which protect a critical coastal highway. These parks were included in forecasts of Warner et al. (2023), but they are not currently nourished on a regular basis. We do not include these state park beaches in this study and refer readers to Warner et al. (2023). All Delaware beaches fall within the Philadelphia USACE district.

Due to the rich military history of Delaware's Atlantic coastline, there are several large offshore zones noted for potential MEC/UXO hazards. While screening practices can reduce the risks associated with MEC/UXO, areas where such dangers are abundant may be removed from consideration as potential sand resources. MEC/UXO have been encountered occasionally on Delaware beaches.

3.1.3.2 Delaware: Past and Current Sand Resources

Delaware's Atlantic beaches have met nourishment demands primarily through offshore sand sources lying within state waters, with a small amount of sand being sourced from in or around the Indian River Inlet just north of Bethany Beach, DE. Many borrow areas have been used and since discontinued in Delaware state waters due poor material quality, habitat concerns, or other factors. Relative to the larger shoals common offshore of Maryland, sand deposits in Delaware tend to be smaller and heterogeneous. This is particularly evident in Rehoboth and Dewey Beach, where the very large Hen and Chickens shoal has been removed from consideration due to habitat concerns. The remaining offshore environment is highly heterogeneous, with thin finger shoals interspersed with muds and gravel beds (Mattheus et al. 2020a).

Delaware Borrow Area F near Fenwick Island has provided high quality beach sand for all beaches in Delaware during interim periods when alternative sources are discontinued. Recent nourishments for Bethany & South Bethany and Rehoboth & Dewey have utilized sand in expanded borrow areas rather than Borrow Area F. To date, Delaware's beaches have not utilized sand resources in federal waters, but this may change as state-managed resources are depleted in coming decades. There is also potential to offset some demand on offshore resources by dredging sand from the in Indian River Inlet ebb and flood shoals, though local regeneration rates and sediment transport dynamics are not fully understood.

Table 10. Past sand usage for the Atlantic beaches of Delaware (USACE Philadelphia District) from 1990 to 2024

Beach	Sand Usage 1990 – 2024 (mcy)	Source Names
Bethany & South Bethany	9.5	DE Borrow Areas E and F, MD Borrow Area 3
Fenwick Island	2.5	DE Borrow Area F, MD Borrow Area 3
Rehoboth & Dewey	7.9	DE Borrow Areas G, F, and B, Hen and Chickens Shoal

3.1.3.3 Delaware: Forecasted Sand Demands and Potential Resources

Table 11. Forecasted additional sand demands for the Atlantic beaches of Delaware
Forecasts span from 2024 to 2050 and 2100. Estimated demand represents the mean of bootstrapped forecast predictions, followed by the quartiles of bootstrapped forecast predictions in parentheses. For simplicity, we only present data from Scenarios 1, 4, and 6 to indicate baseline, medium, and maximum forecast ranges.

Beach	Scenario	Estimated Demand 2050 (mcy)	Estimated Demand 2100 (mcy)
Bethany & South Bethany	S1	9.1 (8-9.8)	25.4 (23.4-26.9)
Bethany & South Bethany	S4	13.4 (10.8-15.6)	59.4 (53.6-65)
Bethany & South Bethany	S6	18.2 (14.8-21.3)	100.6 (93.3-107.9)
Fenwick Island	S1	2.4 (1.4-2.1)	6.7 (4.2-8)
Fenwick Island	S4	7.2 (4.3-9.8)	44.1 (37.2-50.1)
Fenwick Island	S6	12.4 (8.6-16)	85.7 (77.3-93.7)
Rehoboth & Dewey	S1	7 (5.9-7.5)	19.7 (17.6-21.3)
Rehoboth & Dewey	S4	11.4 (8.7-13.7)	54.5 (48.3-59.9)
Rehoboth & Dewey	S6	16.3 (12.7-19.4)	95.8 (88.1-103.4)
Total	S1	18.5 (15.3-19.4)	51.8 (45.2-56.2)
Total	S4	32 (23.8-39.1)	158 (139.1-175)
Total	S6	46.9 (36.1-56.7)	282.1 (274.8-305)

Under our forecast estimates, key state-managed borrow areas in Delaware will be depleted in the mid-21st century. The exact lifetime of these borrow areas is highly uncertain given the ranges of sand demand forecasts and the historical issues of inconsistent sand quality and surficial sand thickness in Delaware Borrow Areas E, G, and B. Improved characterization of seafloor composition and shallow benthic stratigraphy in these borrow areas may help dredgers better target beach quality material contained within, extending the borrow areas' effective lifetimes. Borrow areas and modeled sand resource quality are displayed in Figure 8.

Below is an assessment of Delaware's current borrow areas (south to north):

- **Delaware Borrow Area F:** Current sand supply for Fenwick Island and used in the past for other Delaware beaches with an estimated 32.7 mcy of an initial estimated 40 mcy remaining (USACE 2000). At a conservative estimate of 50% borrow area yield, this resource may be depleted around 2060 (S5 and S6) to 2100 (S1, S2, and S3). Fenwick Island's sand demand forecasts have a particularly wide range (Table 11) relative to other beaches, which complicates estimates of the longevity of this sand resource. The lifespan of this borrow area also depends heavily on whether it becomes the primary borrow area for other Delaware beaches once their currently utilized sand resources are depleted.
- **Indian River Inlet:** The Indian River Inlet accumulates sand south of its jetty, as well as in its ebb and flood shoals. This resource has primarily been used to stabilize the north end of the jetty, which is an erosion hotspot in front of a major coastal highway, and there is a sand bypass facility on the south end. However, the ebb shoal of Indian River Inlet is quite large and may serve as a

sand resource pending additional environmental reviews and public sentiment. It is unclear how much regeneration potential exists for the ebb and flood shoals.

- **Delaware Borrow Area E:** Current sand supply for Bethany & South Bethany with an estimated 19.7 mcy of an initial estimated 25 mcy remaining (USACE 1998). At a conservative estimate of 50% borrow area yield, this resource may be depleted around 2050 to 2060 under all scenarios. However, this borrow area was discontinued in the past due to poor material quality. It was revisited in a recent nourishment, but its history suggests heterogeneous sand resource quality that may reduce its effective lifespan.
- **Delaware Borrow Area B (North):** Current sand supply for Rehoboth & Dewey with an estimated 9.4 mcy of an initial estimated 11 mcy remaining (USACE 2016). At a conservative estimate of 50% borrow area yield, this resource may be depleted around 2040 to 2050 under all scenarios. There are two additional borrow areas south (B South; G) of this, but they have yielded inconsistent material in the past.

Table 12 presents estimated sand deposits within a 10-mile buffer of Delaware's beaches based on classes 5 and 4 (best and second best) from our random forests model of sand resource potential. It is important to note that this is a modeled product and has a substantial amount of associated uncertainty. Additionally, these model estimates do not account for usage conflicts (e.g., fish habitat, already depleted sand units, cultural resources, offshore lease areas) or logistical challenges (e.g., shipping lanes, submerged cables, MEC/UXO). Volumes were conservatively estimated as a uniform thickness of 9 feet for Class 5 sand resource areas and 5 feet for Class 4 sand resource areas.

Table 12. Estimated acreage and volumes of sand deposits within a 10- mile buffer of Delaware's beaches

Sand estimates are based off of total areas of classes 5 and 4 (best and second best) from the sand resource potential model developed in this study. As the potential sand resource quality score reflects both the character and thickness of the resource, volumes were conservatively estimated based on a uniform thickness of 9 feet for class 5 and 5 feet for class 4. Importantly, these are raw model estimates that do not reflect limitations from areas that have been designated as off-limits, areas with MEC/UXO risks, or resources that have been depleted since the collection of bathymetry. Buffers may overlap for adjacent beaches, in which case a sand resource volume is counted for both beaches.

Beach	Class 5 Volume Within 10 miles of Beach Centroid (mcy);(acres)	Class 4 Volume Within 10 miles of Beach Centroid (mcy);(acres)
Fenwick Island	150;10361	101;12505
Bethany/South Bethany	51;3530	72;8964
Rehoboth/Dewey	162;11179	91;11248

The model predicted abundant sand deposits within 10 miles of Fenwick Island and Rehoboth & Dewey, while Bethany & South Bethany have comparably limited nearby sand deposits due to the high seafloor heterogeneity. The area south of Rehoboth & Dewey shares this heterogeneous seafloor environment. The heterogeneity in model predictions in this area likely reflects the morphological composition of seafloor in this area, which is characterized by relatively small finger shoals and flat sheet sands. Encouragingly, the model predictions agreed with mapped geologic characteristics in the area, where thin sheet sands and finger shoals overlay heterogeneous geologic units (e.g., the Beaverdam Formation) and muddy paleovalleys (Mattheus et al. 2020). Encouragingly, model predictions aligned well for features known to contain beach quality sand (e.g., Delaware Borrow Area F, Hen and Chickens Shoal, Great Gull Bank). Delaware Borrow Area F and Fenwick Island shoal in federal waters just past Delaware Borrow Area F account for the majority of estimated sand deposits near Fenwick Island. Both of these sources are noted for MEC/UXO concerns, but they otherwise have no current restrictions on their potential usage. Conversely, most estimated sand volume near Rehoboth & Dewey is accounted for by the Hen and Chickens Shoal which is off-limits as a sand resource due to habitat concerns. Additional sand resources are particularly limited for Rehoboth & Dewey, and accessing sand resources across the Delaware Bay shipping channel would be very logistically complicated. Rehoboth & Dewey utilized Delaware Borrow Area F in the past, which provided beach quality material but is quite distant (<13 miles), making it an expensive option. While Bethany & South Bethany are closer to Delaware Borrow Area F, they may have a similar challenge in securing additional sand resources beyond that. Future studies of sand dynamics may identify opportunities for potential nearshore sand recycling opportunities that could reduce demand on the limited sand deposits offshore.

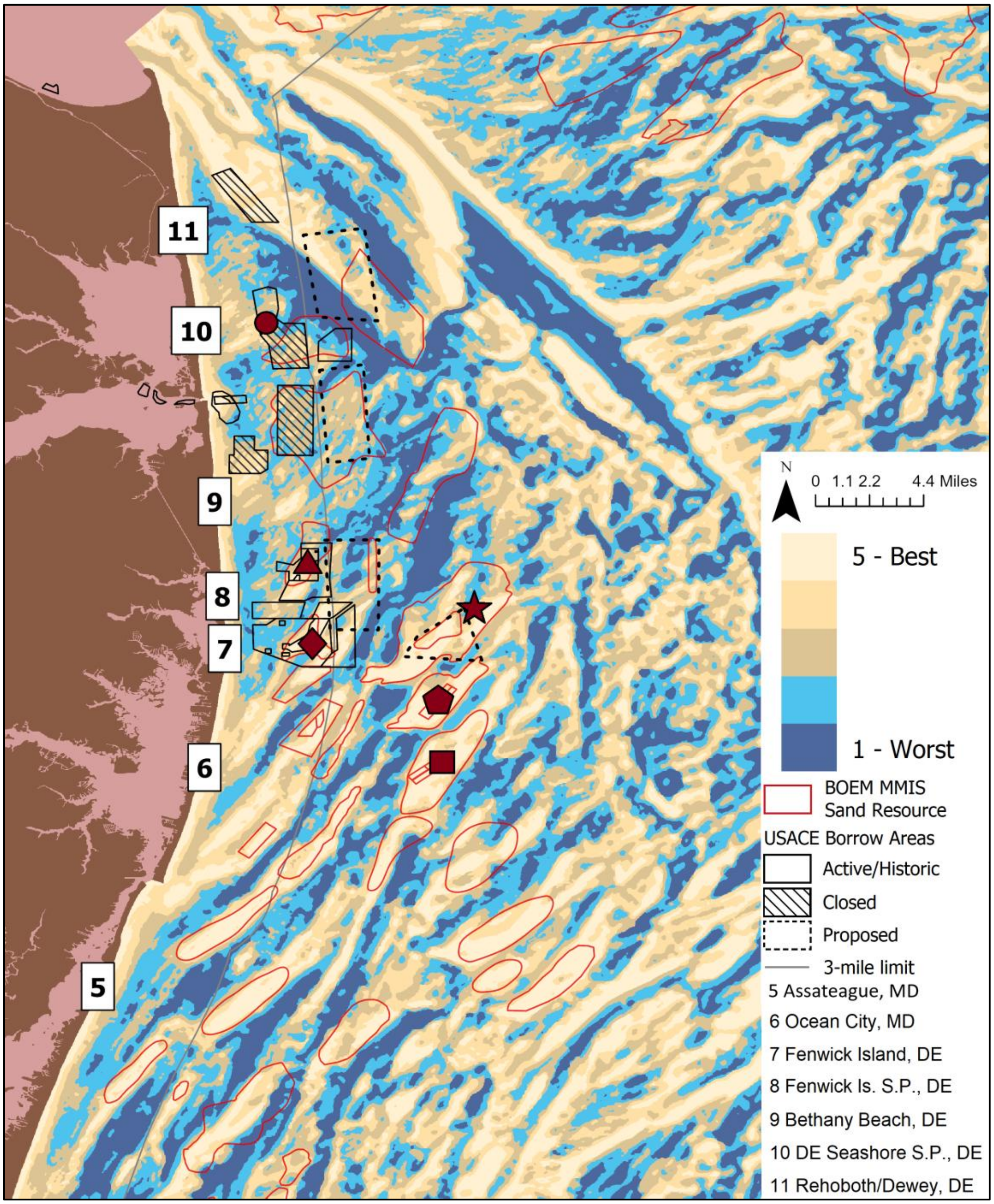

Figure 8. Modeled offshore sand resource potential for Maryland and Delaware

Light tans indicate high predicted quality resources, while blues indicate poor predicted quality. Land and bays are displayed in dark brown and pink, respectively. USACE borrow areas (black solid, hashed, and dashed polygons) are noted with their current status of active/historical (i.e., currently utilized or confirmed and potentially available as future sources), closed (unavailable for future use), or proposed (potential resources that have not yet been approved). Sand resource areas from the BOEM Marine Minerals Information System (red polygons) are also noted, representing areas that have been identified by previous investigations as potential sand resources. Shapes indicate borrow areas discussed in text: Isle of Wight Shoal (square), Weaver Shoal (pentagon), Fenwick Island Shoal (star) and Delaware Borrow Areas F (diamond), E (triangle), and B North (circle).

3.1.4 New Jersey

3.1.4.1 New Jersey: Historical Sand Usage

The New Jersey Atlantic coastline represents the bulk of beach nourishment within our study area. The majority of this coastline is highly developed, serving as a mix of full-time residential communities and beach towns that support a strong coastal economy. The shoreline is made up of distinct barrier island units separated by inlets, with back bays, harbors, and tidal marshes in the southern portion of the state. Although the barrier islands may contain multiple distinct municipalities, modern beach nourishment and coastal protection efforts are generally applied across whole barrier islands. The New Jersey beaches in our study were grouped in Table 1 (Section 2.1.1). Asbury Park/Manasquan and Sea Bright beach units fall within the New York USACE district, while the other New Jersey beaches are within the Philadelphia district. In addition to commercial and residential development, the New Jersey coastline contains US Coast Guard and National Guard sites as well as several public beach parks and wildlife refuges.

Many beaches in New Jersey underwent major beach and dune reconstruction projects in the years following Hurricane Sandy (2012), which caused widespread coastal erosion and property damage. In some cases, these reconstruction events took place just 10 years after major reconstructions in the early 2000s when the USACE began widespread New Jersey Shore Protection programs across the state. This highlights the reason for including major erosion events in our sand demand forecasts, as they can prompt major short-term increases in offshore sand needs beyond those in established coastal protection plans. Hurricane Sandy also raised public awareness on coastal erosion and beach nourishment. The number of beaches receiving periodic nourishments increased substantially following the storm, which has greatly increased demand for sand resources along the New Jersey coastline.

3.1.4.2 New Jersey: Past and Current Sand Resources

New Jersey, particularly in the Philadelphia USACE district, has heavily utilized several nearshore sand sources from inlets, harbors, and ebb shoals. The state routinely dredges to maintain inland waterways, and many inlet ebb and flood shoals show regeneration potential. However, habitat concerns and pushback from recreational fishing communities have limited the use of some of these sources. Additional sand resources have been utilized offshore in state waters, including the very large and now discontinued Sea Bright Borrow Area in the north end of the study area. Sea Bright Borrow Area was discontinued due to issues of seafloor armoring, causing the resource to yield only a fraction of its anticipated usable volume. To date, many potential borrow areas have been identified in federal waters, but their use has been limited.

Table 13. Past sand usage for the Atlantic beaches of New Jersey (USACE Philadelphia District) from 1990 to 2024

Beach	Sand Usage 1990 – 2024 (mcy)	Source Names
Absecon Island	14.2	NJ Borrow Area H, Absecon Inlet
Avalon	11.6	Unknown Borrow Area, Hereford Inlet, Townsends Inlet
Barnegat Peninsula	10.7	Manasquan Borrow Area A and D
Brigantine	8.3	Brigantine Inlet
Cape May	9.7	NJ Borrow Areas K, 45, and M1
Long Beach Island	21.2	NJ Borrow Areas D1 and D2
Ludlam Island	12.3	Corson Inlet (C1), L1, and L3, Townsend Inlet
Ocean City, NJ	23.9	Great Egg Inlet
Wildwood	2.3	Hereford Inlet, South Wildwood Beach

Table 14. Past sand usage for the Atlantic beaches of New Jersey (USACE New York District) from 1990 to 2024

Beach	Sand Usage 1990 – 2024 (mcy)	Source Names
Asbury Park & Manasquan	6.6	Sea Bright Borrow Area 1
Sea Bright	35.2	Sea Bright Borrow Area 1

3.1.4.3 New Jersey: Forecasted Sand Demands and Potential Resources

Table 15. Forecasted additional sand demands for the Atlantic beaches of New Jersey (Philadelphia USACE District)

Forecasts span from 2024 to 2050 and 2100. Estimated demand represents the mean of bootstrapped forecast predictions, followed by the quartiles of bootstrapped forecast predictions in parentheses. For simplicity, we only present data from Scenarios 1, 4, and 6 to indicate baseline, medium, and maximum forecast ranges.

Beach	Scenario	Estimated Demand 2050 (mcy)	Estimated Demand 2100 (mcy)
Absecon Island	S1	13.1 (12.2-13.7)	36.6 (34.4-38.2)
Absecon Island	S4	17.1 (14.7-19.3)	68.5 (63-73.4)
Absecon Island	S6	21.7 (18.6-24.6)	109.7 (102.8-116.6)
Avalon	S1	9.5 (8.4-10.1)	26.8 (24.8-28.3)
Avalon	S4	13.7 (11.2-15.9)	60.5 (54.7-66.2)
Avalon	S6	18.4 (15.2-21.5)	101.7 (93.9-109.1)
Barnegat Peninsula	S1	30.5 (27.6-33.1)	83.2 (78.9-87.4)
Barnegat Peninsula	S4	33.3 (29.8-36.6)	108.3 (101.2-115.3)
Barnegat Peninsula	S6	37.7 (33.5-41.6)	156.1 (147.8-164.1)
Brigantine	S1	7.5 (6.2-8.2)	21.3 (19.3-22.8)
Brigantine	S4	11.9 (9.2-14.1)	56.4 (50.1-62.2)
Brigantine	S6	17 (13.6-20.2)	99.3 (91.8-106.8)
Cape May	S1	4.8 (3.9-4.6)	13.7 (11.4-15)
Cape May	S4	9.3 (6.7-11.5)	49.4 (42.6-55.8)
Cape May	S6	14.2 (10.6-17.7)	90 (81.7-98.4)
Long Beach Island	S1	11.2 (9.6-12.5)	28.3 (25.7-30.6)
Long Beach Island	S4	15.4 (12.6-17.9)	64.7 (58.1-70.7)
Long Beach Island	S6	21 (17.2-24.3)	113.5 (105.9-120.8)
Ludlam Island	S1	6.7 (5.5-7.4)	18.6 (16.5-20.1)
Ludlam Island	S4	11.2 (8.4-13.7)	54.5 (48.2-60.7)
Ludlam Island	S6	16.3 (12.9-19.4)	98.3 (90.7-106)
Ocean City (NJ)	S1	15.6 (14.3-16.4)	41.7 (39.7-43.4)
Ocean City (NJ)	S4	19.3 (16.8-21.3)	72.7 (67.4-77.8)
Ocean City (NJ)	S6	23.9 (20.9-26.8)	114.2 (107.1-120.8)
Wildwood	S1	9.1 (7.8-9.9)	25.7 (23.7-27.4)
Wildwood	S4	13.2 (10.5-15.3)	60 (53.9-65.6)
Wildwood	S6	18 (14.7-21.2)	103.2 (96-110.2)
Total	S1	108.7 (95.5-115.9)	295.9 (274.4-313.2)
Total	S4	144.4 (119.9-165.6)	595 (539.2-647.7)
Total	S6	188.2 (157.2-217.3)	986 (917.7-1052.8)

Table 16. Forecasted additional sand demands for the Atlantic beaches of New Jersey (New York USACE District)

Forecasts span from 2024 to 2050 and 2100. Estimated demand represents the mean of bootstrapped forecast predictions, followed by the quartiles of bootstrapped forecast predictions in parentheses. For simplicity, we only present data from Scenarios 1, 4, and 6 to indicate baseline, medium, and maximum forecast ranges.

Beach	Scenario	Estimated Demand 2050 (mcy)	Estimated Demand 2100 (mcy)
Asbury Park - Manasquan	S1	5.5 (4.3-6.3)	14.6 (12.3-16.3)
Asbury Park - Manasquan	S4	10.4 (7.5-12.7)	27 (22.9-30.9)
Asbury Park - Manasquan	S6	15.6 (12.1-18.9)	95.7 (88.2-103)
Sea Bright	S1	21.8 (20.2-23.1)	59.4 (57-61.6)
Sea Bright	S4	25.1 (22.7-27.2)	72.9 (68.9-76.8)
Sea Bright	S6	29.3 (26.2-32.3)	128.3 (121.8-134.8)
Total	S1	27.3 (24.5-29.4)	74 (69.3-77.9)
Total	S4	35.5 (30.2-39.9)	138.8 (126.8-150.2)
Total	S6	44.9 (38.3-51.2)	224 (210-237.8)

Like other states in the project area, forecasts of sand demand in New Jersey vary widely across different scenarios, especially by 2100 (Tables 15 and 16). The 2050 forecasts vary less across the different scenarios than those in Delaware. The largest source of uncertainty for the longevity of current sand resource supplies in New Jersey is the degree to which harbor dredging and inlet shoals can continue to supply sand or at least offset demand on non-renewable offshore sources. This uncertainty is compounded by potential increases in sand accretion in and around inlets due to sand being added to the nearshore system, as was observed for the Shark River Inlet near Asbury Park, NJ (Beck and Kraus 2011). This effect suggests a benefit of increasing sand regeneration rates from nearshore sand deposits, but it also poses a cost of necessitating more frequent dredging to maintain navigation channels. Additional studies of local sediment dynamics following nourishments will improve our understanding of nearshore sand dynamics in the state, helping coastal managers better plan for sand resource needs. Borrow areas and modeled sand resource quality are displayed in Figures 9, 10, and 11.

Below is an assessment of New Jersey’s current borrow areas (south to north):

- **New Jersey Borrow Area K:** The current sand supply for Cape May has been subdivided into three areas and a small extension area. Some of the extension areas have been made off-limits due to fisheries concerns, complicating estimates of this borrow area’s longevity. An estimated 2 to 3 mcy remain (USACE 2018), with more potentially available pending additional expansions. This should sustain Cape May’s relatively low sand demand into 2040 to 2050, which is roughly in line with estimates from USACE.
- **Wildwood Beach:** Wildwood has experienced hotspot erosion on the north end of the island along and extensive sand accretion on the south end. This presents an interesting opportunity for sand backpassing to combat hotspot erosion and reduce the overabundance of sand to the south. It is unclear what amount of future sand demand this will offset, but it should reduce some demand pressure on other sources if these erosion and deposition patterns persist.

- **Hereford Inlet:** This ebb shoal was used in the past for nourishment projects for both Wildwood and Avalon. The total estimated volume is roughly 8.8 mcy (USACE 2014), but it is a dynamic system with potential for regeneration. This sand resource was recently placed off-limits due to fisheries concerns, and its future as a potential sand resource is uncertain.
- **Townsends Inlet:** This ebb shoal and inlet was utilized in recent nourishment projects for Avalon with an estimated volume of 2.4 mcy, though this estimate is quite old (USACE 1997). This sand resource is believed to regenerate over time, complicating estimates of its potential longevity. Its current estimated volume should sustain demand for 1 to 2 additional nourishment cycles, and USACE notes a major sand deficit for Avalon in the coming decades.
- **Corson Inlet (C1):** This inlet and its associated shoals were dredged to supply sand to Ludlam Island beaches in the past, and it is considered as a potential sand supply for future nourishments. The inlet is highly dynamic. Sand deposits surrounding the inlet regenerate but shift frequently, making volume and regeneration rate estimates difficult. Corson Inlet has high densities of surf clams and is a popular recreational fishing area, which complicates its utility as a sand resource. However, its dynamic nature may limit benthic habitat impacts of dredging, and dredging to maintain inlet navigation is necessary at times.
- **New Jersey Borrow Areas L1 and L3:** The current sand supply for Ludlam Island contains an estimated combined remaining total of 16.2 mcy of usable material, which is much lower than the initial estimated combined volume of 28.7 mcy (USACE 2001). Borrow areas L1 and L3 sit just inside the 3-mile limit of state waters, but an additional borrow area L2 sits in federal waters and has not been utilized. These borrow areas have had some concerns with material quality, which may cause them to be discontinued prematurely. At a conservative estimate of 50% borrow area yield, this resource may be depleted around 2050 to 2060 under scenarios 1-3 and around 2040 to 2050 under scenarios 4-6. The current USACE coastal protection plan is scheduled to use these borrow areas until 2064, but it is noted that additional resources may be needed to meet demand before then.
- **Great Egg Harbor Inlet:** This inlet is the current and frequent sand supply for Ocean City, NJ. This sand source regenerates rapidly, making it difficult to estimate its lifespan and total potential volume. Ocean City, NJ has relied heavily on this sand resource rather than extracting sand from nearby borrow area M8 in federal waters. It is uncertain how long this sand resource will be able to sustain demand for Ocean City, NJ, but it will likely continue to at least alleviate some demand pressure on offshore sources in the area.
- **New Jersey Borrow Area H:** The current sand supply for Absecon Island contains an estimated remaining 6.7 mcy, though we were unable to locate an initial estimate. This sand resource will likely be depleted by 2030 or 2040 based on all forecast scenarios. Limited information was available for this borrow area. There are ongoing discussions regarding the expansion of this borrow area, and steps have been taken to minimize potential spatial conflicts with offshore wind development in the future. USACE is investigating additional borrow areas in federal waters to the north (i.e., New Jersey Borrow Area G).
- **Absecon Inlet:** This inlet was used as an additional sand resource for Absecon Island in a recent nourishment. Its close proximity to the erosion hotspot on the north end of Atlantic City makes this sand resource an attractive option for small scale nourishments there. While this resource will help alleviate demand pressure on Borrow Area H, its regeneration rate and ability to supply beach quality material in the future is uncertain.

- **Brigantine Inlet:** This current source for Brigantine Island has supplied an estimated 4.6 mcy of sand over the past 15 years. The regeneration rate of this sand resource is uncertain, but Brigantine's sand demand is relatively low compared to other New Jersey beaches (< 1 mcy every 4-5 years recently). Potential for sand backpassing from the accreting southern portion of the island may help sustain Brigantine's sand demand into the future, though accelerating coastal erosion rates in the late 21st century may require additional resources to mitigate.
- **New Jersey Borrow Areas D1 and D2:** These current sand sources for Long Beach Island nourishment projects have an estimated combined total of 17.1 mcy of sand remaining of an initial estimated 25 mcy (USACE 1999). While this is a large volume of sand, Long Beach Island has one of the largest historical and forecasted beach nourishment demands within the project area. Additionally, Area D1 was discontinued due to high risks of MEC/UXO, though it may be revisited in the future. At a conservative estimate of 50% borrow area yield, this resource may be depleted around 2040 to 2050 under all forecast scenarios. Investigations into potential dredging of Little Egg and Barnegat Inlets, as well as borrow area expansions, are ongoing. However, the presence of cables and MEC/UXO in the nearshore and offshore environments of Long Beach Island complicates efforts to identify additional resources.
- **Manasquan Borrow Areas (A, B, D, E, F1 and F2):** The now discontinued Borrow Area A for Barnegat Peninsula reconstruction has an estimated 8.9 mcy of sand remaining (USACE 2002). This borrow area was discontinued due to reports of heavy shell and gravel armoring, which was also reported in the adjacent Manasquan Borrow Area E. Borrow Area D was also used as a sand source, but had issues with frequent seams of incompatible very fine material. There is a small Manasquan Borrow Area B nearby with limited sand availability due to fisheries concerns. There have been investigations into the large Borrow Areas F1 and F2 further offshore in federal waters, which may be utilized in the future (Gagliano et al. 2018). These borrow area volumes have not been fully assessed, but they may contain over 50 mcy combined. However, there are also concerns about Borrow Areas F1 and F2 due to their proximity to popular fishing areas.
- **Sea Bright Borrow Area:** This very large borrow area has been utilized for both Sea Bright and Asbury Park & Manasquan beaches. With an estimated initial volume of 87 mcy, this borrow area has encountered surficial coarsening issues that limit sand accessibility after only 32 mcy were removed (USACE 2025). This issue is due to MEC/UXO screens on dredge intakes, which highlights the issues described in Section 2.2.3 of this report. There is always a risk of greatly overestimating a sand resource's available volume due to unforeseen circumstances that arise years later. Investigations into additional sand resources for Sea Bright and Asbury Park & Manasquan beaches are ongoing, but this borrow area remains active for the time being.

Table 17 presents estimated sand deposits within a 10-mile buffer of New Jersey's beaches based on classes 5 and 4 (best and second best) from our random forests model of sand resource potential. It is important to note that this is a modeled product and has a substantial amount of associated uncertainty. Additionally, these model estimates do not account for usage conflicts (e.g., fish habitat, already depleted sand units, cultural resources, offshore lease areas) or logistical challenges (e.g., shipping lanes, submerged cables, MEC/UXO). Volumes were conservatively estimated as a uniform thickness of 9 feet for Class 5 sand resource areas and 5 feet for Class 4 sand resource areas.

Table 17. Estimated acreage and volumes of sand deposits within a 10- mile buffer of New Jersey beaches

Sand estimates are based off of total areas of classes 5 and 4 (best and second best) from the sand resource potential model developed in this study. As the potential sand resource quality score reflects both the character and thickness of the resource, volumes were conservatively estimated based on a uniform thickness of 9 feet for class 5 and 5 feet for class 4. Importantly, these are raw model estimates that do not reflect limitations from areas that have been designated as off-limits, areas with MEC/UXO risks, or resources that have been depleted since the collection of bathymetry. Buffers may overlap for adjacent beaches, in which case a sand resource volume is counted for both beaches.

Beach	Class 5 Volume Within 10-miles of Beach Centroid (mcy);(acres)	Class 4 Volume Within 10-miles of Beach Centroid (mcy);(acres)
Cape May	152;10436	137;16959
Wildwood	135;9268	106;13124
Avalon	119;8217	92;11347
Ludlam Island	127;8770	107;13274
Ocean City	94;6459	96;11948
Absecon Island	91;6279	104;12856
Brigantine	151;10394	166;20545
Long Beach Island	64;4417	77;9593
Barnegat Peninsula	66;4560	68;8468
Asbury Park/Manasquan	114;7839	100;12413
Sea Bright	102;6996	101;12508

The model predicted relatively abundant beach quality offshore sand deposits within 10 miles of Cape May, Wildwood, Ludlam Island, and especially Brigantine (Figures 9 and 10). Model predictions aligned with known or suspected sandy shoal features in these areas. Barnegat Peninsula and Long Beach Island are of particular concern, as they have relatively high forecasted sand demand and relatively limited predicted high quality offshore sand volume (Figures 10 and 11). Model predictions suggested several large areas of poor material in both central and north New Jersey regions that stretch from roughly 1 to 6 miles offshore. All these areas have relatively little bathymetric variation, and the poor predicted sand resource quality may be a result of the model relying solely on bathymetric derivatives. However, Manasquan Borrow Areas A, D, and E all fall within one of these poor predicted resource areas (Figure 11), and all are borrow areas noted for sand quality issues in the past. As discussed previously, many beaches in New Jersey have met or at least offset their sand resource demand using inlet and harbor dredge materials, and it is uncertain to what degree these regenerative resources will continue to sustain demand far into the future. Offshore New Jersey has a very high density of commercial and recreational fishing activities, which may cause usage conflicts for proposed sand resources. Additionally, nearly the entire Atlantic coastline of New Jersey is highly developed and forecasted sand demand is high in almost every community. Balancing the demands of neighboring beaches may become challenging in the coming decades.

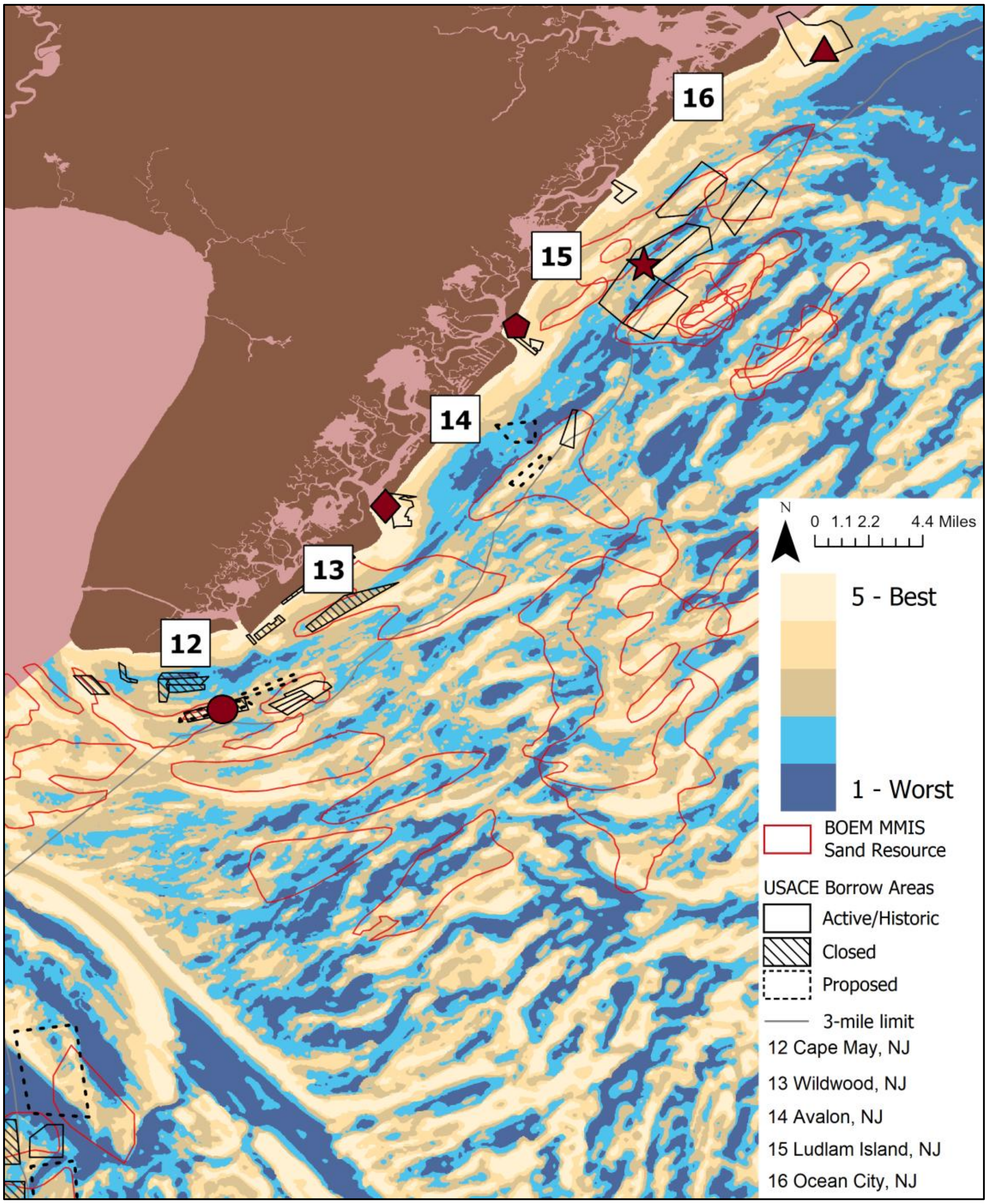

Figure 9. Modeled offshore sand resource potential for southern New Jersey

Light tans indicate high predicted quality resources, while blues indicate poor predicted quality. Land and bays are displayed in dark brown and pink, respectively. USACE borrow areas (black solid, hashed, and dashed polygons) are noted with their current status of active/historical (i.e., currently utilized or confirmed and potentially available as future sources), closed (unavailable for future use), or proposed (potential resources that have not yet been approved). Sand resource areas from the BOEM Marine Minerals Information System (red polygons) are also noted, representing areas that have been identified by previous investigations as potential sand resources. Shapes indicate borrow areas discussed in text: New Jersey Borrow Area K (circle), Hereford Inlet (diamond), Townsend Inlet (pentagon), New Jersey Borrow Areas L1 and L3 (star), and Great Egg Inlet (triangle).

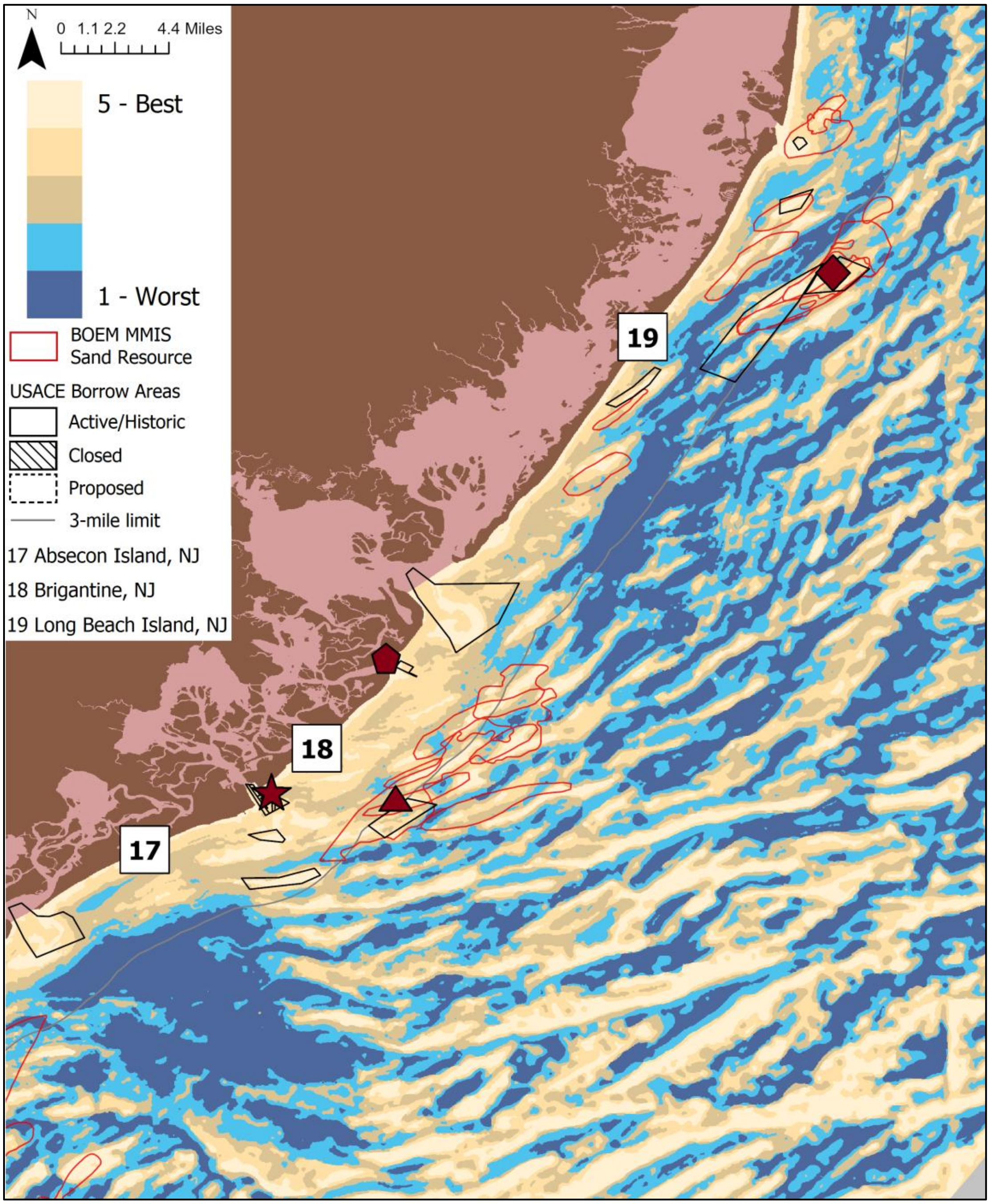

Figure 10. Modeled offshore sand resource potential for central New Jersey

Light tans indicate high predicted quality resources, while blues indicate poor predicted quality. Land and bays are displayed in dark brown and pink, respectively. USACE borrow areas (black solid, hashed, and dashed polygons) are noted with their current status of active/historical (i.e., currently utilized or confirmed and potentially available as future sources), closed (unavailable for future use), or proposed (potential resources that have not yet been approved). Sand resource areas from the BOEM Marine Minerals Information System (red polygons) are also noted, representing areas that have been identified by previous investigations as potential sand resources. Shapes indicate borrow areas discussed in text: Absecon Inlet (star), Borrow Area H (triangle), Brigantine Inlet (pentagon), Borrow Areas D1 and D2 (diamond). Some linear artifacts in the model predictions are evident off Long Beach Island, NJ.

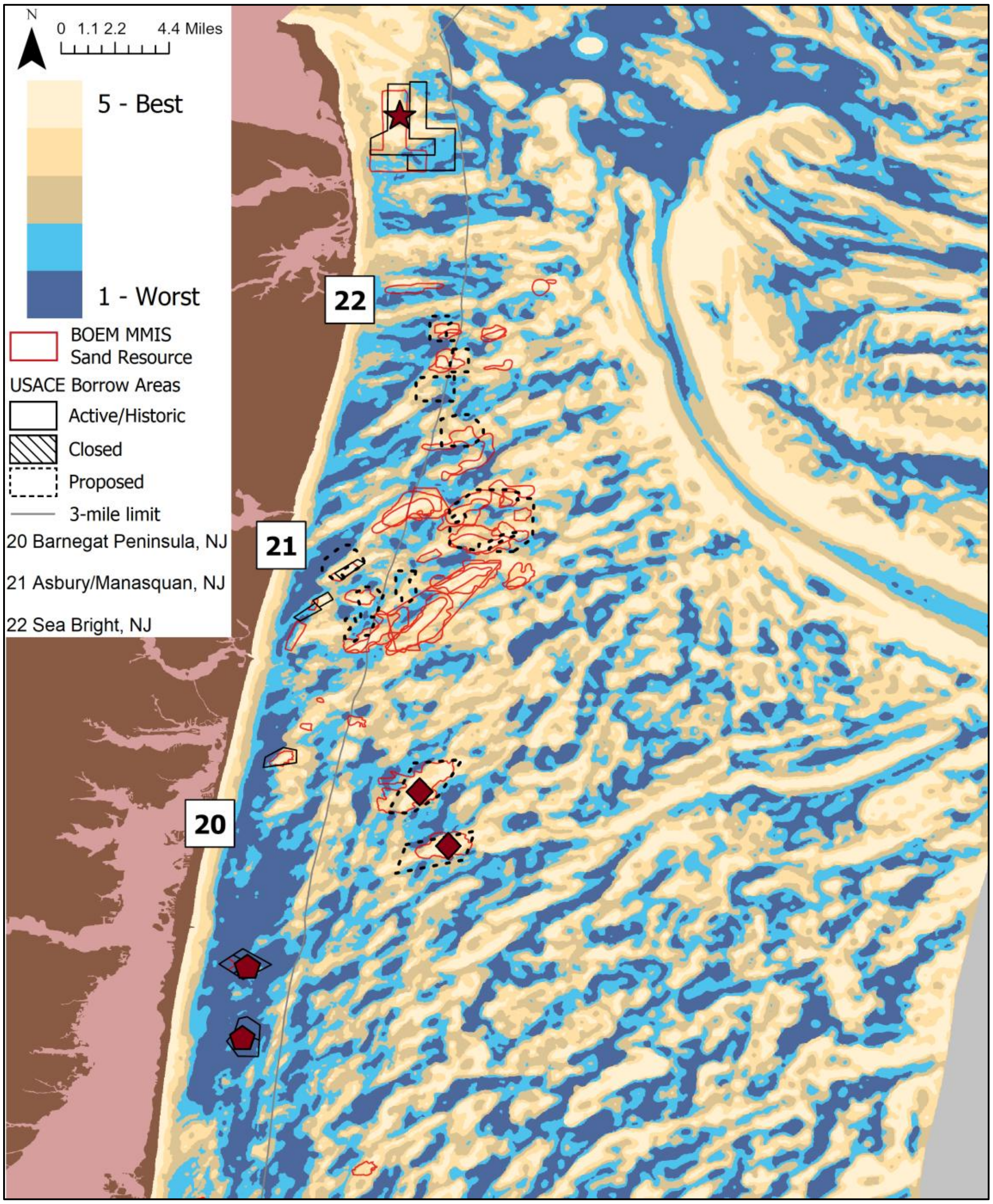

Figure 11. Modeled offshore sand resource potential for northern New Jersey
Light tans indicate high predicted quality resources, while blues indicate poor predicted quality. Land and bays are displayed in dark brown and pink, respectively. USACE borrow areas (black solid, hashed, and dashed polygons) are noted with their current status of active/historical (i.e., currently utilized or confirmed and potentially available as future sources), closed (unavailable for future use), or proposed (potential resources that have not yet been approved). Sand resource areas from the BOEM Marine Minerals Information System (red polygons) are also noted, representing areas that have been identified by previous investigations as potential sand resources. Shapes indicate borrow areas discussed in text: Manasquan Borrow Areas A/E (lower pentagon), Manasquan Borrow Area D (upper pentagon), Manasquan Borrow Areas F1 and F2 (diamonds), and Sea Bright Borrow Area (star).

3.1.5 Comparisons to USACE Sand Needs Forecasts

Our estimates of sand resource demand generally exceed those made by the USACE for the mid-21st century, although USACE forecasting horizons do not align exactly to the decadal statistics generated in this study. These discrepancies may be a result of time horizons considered and methodologies. USACE sand needs forecasts are based on site-specific coastal engineering studies, while the estimates in this study are forecasted based on historical trends and hypothetical increases in future coastal erosion risks driven by sea level rise and coastal storm hazards. Our forecasts exceeded those of the USACE across all districts and scenarios, with our high erosion scenarios predicting sand demand far above those of the USACE. For example, the USACE estimates an additional sand demand of 250 mcy for the Philadelphia District by 2080 (Bocamazo 2025), while our forecasts estimate that 250 mcy will be needed between 2050 and 2060, depending on the scenario. Conversely, USACE forecasts for sand needs in the Baltimore District are comparable to ours, but the forecasts only go to 2044. Our forecasts tend to diverge after about 2050.

This is not to say that our forecasts are more accurate, but it does highlight how different methodologies can create very different forecasts as they extend further into the future. Looking forward, it is important for coastal managers to have a better understanding of forecast ranges and what potential sand resources exist to allow for adaptable, proactive coastal protection strategy. Human behavior, public sentiment, and funding availability will all affect how much sand is ultimately dredged and placed in the coming decades.

3.2 Discussion from Mid-Atlantic Regional Sand Resources Coordination Meeting

The DGS hosted a regional sand resources coordination meeting as part of this cooperative agreement. The meeting drew coastal managers, engineers, and environmental researchers from across the Mid-Atlantic and featured presentations from other regional BOEM cooperative agreements, academia, and other federal partner agencies. The meeting also featured a lengthy open discussion for sharing insights, challenges, and successes for beach nourishment activities across the region. This section summarizes the key points of these discussions. Full meeting notes and presentation slides are included in Appendix B.

3.2.1 Data Needs

The discussions identified key data needs to better manage offshore sand resources, as well as potential offshore mineral sands and aggregate resources. Data needs span from need for better economic resource assessments to better geological characterizations of the offshore environment. Specific identified data needs included:

- **Improved monitoring of pre- and post-storm beach profiles:** This will enhance our understanding of erosion rates and how different events affect beaches in different ways. Advances in satellite and drone-based remote sensing may help achieve this.
- **Improved data sharing and transparency with offshore wind projects:** Coastal managers have had mixed success in gaining access to the abundant core and geophysical datasets collected by wind energy developers. Such data would be very valuable for modeling efforts like the one presented in this study, especially considering that offshore wind energy projects are primarily located in areas with sparse seafloor data.

- **Reanalysis of geologic datasets:** Programs like the USGS's National Geological and Geophysical Data Preservation Program are making older, paper-based geological datasets machine readable and available for analysis with new computational tools. Reanalysis of these datasets could provide new insights into coastal and shelf geology.
- **Better economic analysis of beach nourishment**: Improving cost/benefit estimates for beach nourishment as a practice will help BOEM better balance different offshore activities. Beyond direct project costs (e.g., dredging contracts, environmental impact assessments), better quantification of the value of sand as a resource and costs associated with finding new sand resources are needed.

3.2.2 Public Outreach and Engagement

Public outreach and engagement are critical components of beach nourishment and coastal management. Beyond addressing the concerns of beach communities and environmental groups, there is clearly a need to improve public understanding of coastal hazards and engineering solutions in general. Specific identified challenges and successes included:

- **Public sentiment changes through time:** Public support of beach nourishment tends to be reactive. Recent storms and visible erosion will often build public support, while periodic small nourishments may have less support. In some cases, beach nourishment is viewed as a "rich people problem" until the erosion is so severe that it impacts local economies or infrastructure.
- **Improve media relations for coastal scientists and engineers:** A major public engagement challenge is that science and engineering communities have historically had limited training and encouragement for working with the press. This is one of the best ways to disseminate information to the public, but it requires trust between journalists and coastal managers. Additionally, public communications from coastal science and engineering communities are lagging behind short-format media trends.
- **Environmental literacy is generally low:** There is a general lack of public understanding of concepts like barrier island formation, continental shelf processes, and beach and dune ecology. Developing plain language educational materials to accompany beach nourishment activities could help integrate these concepts into school curricula and provide better context for local communities.

3.2.3 Spatial Conflicts

Spatial conflicts on the continental shelf can greatly limit access to sand resources. This issue is particularly evident on the Gulf Coast, where active and derelict energy infrastructure has made many potential sediment resources unusable. As offshore energy projects progress in the Mid-Atlantic, it is critical to minimize such spatial conflicts that may make resources inaccessible. Specific notes on spatial conflicts included:

- **Challenges to USACE oversight:** Preventing activities in federal waters that may lead to indefinite preclusion of access to a sand resource requires USACE review if a sand resource has been officially considered for beach nourishment in project authorizations and Chief's Reports. Such activities may include laying a submerged cable, placing a footing, or sinking objects for artificial reef habitat. This creates a potential issue for long-term planning and protection of offshore sand resources, as these official documents require extensive preparation and research. Many potential sand deposits have not been considered or evaluated in this fashion, which makes regional, long-term sand resources planning challenging.

- **Lack of multi-use areas:** Historically, space on the continental shelf was leased (e.g., for oil and gas, pipelines, wind energy, artificial reefs) in a manner that did not consider potential for multiple current or future uses. This is exemplified in areas of the Gulf Coast where former oil infrastructure has left a patchwork of exclusion zones that have now greatly reduced the accessibility of sediment resources and, where accessible, the efficiency of resource dredging. Adaptive offshore management strategies could allow occasional sand harvesting from many resources rather than repeated dredging of single resource areas, but this will require proactive investigations into multiple potential uses on the OCS could optimize long-term spatial planning. While this would require a significant investment in terms of geological and habitat surveys, but distributing dredging activities across many sources would reduce the frequency of benthic habitat disturbances.

4 Conclusions

4.1 Sand Resources in the Mid-Atlantic

Demand for sand resources to support beach nourishment programs has increased substantially across the Mid-Atlantic Region in the early 21st century. Our forecasts suggest that this demand will continue to increase as sea level rise and shifts in coastal storms cause increasing beach erosion risks. The beaches included in the study region used an estimated 215 mcy of sand from 1990 to 2024. Depending on the forecasting scenario used, we estimate that the region will require an additional 421 to 602 mcy of sand by 2050, or 780 to 2,310 mcy by 2100, assuming that beach nourishment is still the coastal stabilization strategy of choice at those times. To put this volume into perspective, it is enough sand to bury the entirety of Manhattan Island 30 to 100 feet deep. Securing additional sand resources and strategically planning for their sustainable utilization is critical to support ongoing coastal management within this study region.

The large regional totals of sand demand do not reflect the heterogeneity of demand and resource availability for the different beaches considered in this study. Several beaches are relatively secure with regards to long-term sand resource supplies of current sand sources (e.g., Wallops Island, VA, Fenwick Island, DE), while others are actively trying to identify additional resources to meet demand in the coming decades (e.g., Sea Bright, NJ). Additionally, many currently utilized borrow areas across the Mid-Atlantic intersect with areas of concern for MEC/UXO hazards or may have heterogeneous material quality. Few beaches have backup sources ready for use if a current sand resource were suddenly placed off-limits, and the process of identifying new resources, assessing environmental impacts, soliciting public feedback, contracting a dredging company, and obtaining necessary permits can take years. This poses a major coastal resiliency risk, as beach communities may be left without a source of sand and exposed to greater storm surge and economic risks as a result.

Unlike the Gulf Coast OCS, derelict energy infrastructure and major seafloor hazards are relatively sparse in the Mid-Atlantic OCS. Though this relative freedom from submerged infrastructure (e.g., pipes, cables, footings) is encouraging for long-term coastal resource planning, increasing interest in offshore wind energy and associated submarine cable corridors have already begun to affect sand resource access and spatial planning. Our model suggests that potential high quality, albeit unconfirmed, beach sand resources are common across the region, and the model predictions show good spatial agreement with known sand resources and other modeled shoal products. Strategic planning to limit the possibility of sand resource inaccessibility, especially within economically feasible buffer distances from major beaches, should be prioritized, which will minimize spatial conflicts between habitat conservation efforts, offshore renewable energy projects, and sand resource demands.

4.2 Research priorities

We emphasize two primary research priority areas to enhance our understanding of sand resource availability and support long-term sustainable coastal planning in the Mid-Atlantic:

First, there is a need for additional geotechnical and geological data collection, particularly in the federally managed portions of the OCS where data is sparse. Additional data collection will provide better confirmation of suspected sand resources, but care should be taken to collect data representative of all seafloor morphological features. As discussed in Section 2.3.1.4, offshore core datasets have become increasingly biased towards high quality beach sand resources because coring campaigns are increasingly motivated by identifying or confirming sand resources for beach nourishment. This bias results in an unbalanced dataset that makes statistical modeling and analysis of seafloor sediments difficult, which limits our scientific understanding of OCS sediment distributions. Given an increasing focus on marine mineral resources beyond sand (e.g., critical minerals, aggregates), it is important that we better characterize the wide array of seafloor environments, subfloor stratigraphic units, and morphological processes beyond those associated with beach quality sand deposits. Recent advances in machine learning and geospatial data science could provide new insights into the benthic habitats and sediments of the OCS, but these techniques require quality, balanced datasets to provide robust models and predictions.

Second, nearshore sand dynamics, especially in the aftermath of major nourishment and erosion events, are poorly understood. Thirty years of beach nourishment has shifted large quantities of offshore sand into the littoral zone, but the fate of this sand after placement and subsequent erosion is uncertain. Nearshore sediment dynamics vary locally due to differences in inlet or shoreline morphology, tidal ranges, nourishment history, and man-made structures (e.g., jetties, groins). In some cases, new shoals may form around inlets due to the sudden influx of material. In others, inlets may fill in with sediment faster than they used to, requiring more frequent maintenance dredging. Understanding the complex nearshore dynamics of beaches along the Mid-Atlantic coastline is a major challenge that requires local-scale investigations and tailored solutions. We argue that it is a challenge worth taking, as it will help identify opportunities for sand recycling and backpassing that could reduce demand pressure on offshore resources. This would provide economic benefits, as pumping sand from dredges far offshore is very expensive, and environmental benefits, as reducing ecological disturbances from dredging would allow benthic habitats more time to recover. Other parts of the world are investigating innovative approaches for beach nourishment and shoreline protection that reduce financial and environmental costs. For example, the Sand Engine in the Netherlands differed from traditional beach nourishment as used strategic placement of a large volume of sandy material (>20 mcy) and then allowed the placement to evolve naturally, rather than attempting to fully construct an idealized beach-dune profile (Schipper et al. 2016). This has created a system that can nourish beaches down current, form offshore sandbars and sand groins that attenuate wave energy, and create lagoon, dune, and tide pool habitats. Despite the large initial volumes of material needed, such constructions require less onshore beach grading and may last for well over a decade, reducing construction costs and the frequency of associated ecological disturbances. Another innovative approach was the construction of submerged sandbars and sand groins in Jinsha Bay, China, which has demonstrated reduced beach erosion, gradual beach sand nourishment, and low construction costs (Fan et al. 2025). Naturally, these alternative strategies still require a solid understanding of local nearshore currents and sediment dynamics.

4.3 Closing Remarks

Beach nourishment and coastal stabilization are multifaceted issues facing much of the Mid-Atlantic and developed coastlines worldwide. Beach communities in the Mid-Atlantic support strong coastal economies, and beach and dune systems provide critical habitat for many animal species. While it is important to protect and maintain beaches, the financial and environmental costs of doing so are high. These costs may be minimized by long-term strategic planning to guide sustainable resource and habitat management.

The analysis presented in this study indicates that some beaches have secured sand resources to support long-term beach nourishment demands, while others are actively searching for additional sand resources to meet demand. It is important for communities to protect and secure sand resources beyond what are needed in the short term (e.g., 1-2 nourishment cycles) to avoid potential loss of access to resources and use conflicts. Utilizing nearshore, regenerative sand resources is an excellent way to reduce demand pressure on offshore resources, but overreliance on these dynamic areas could leave communities without adequate sand volumes if additional potential resources are not secured.

Our analysis also highlights the massive volumes of sand that will be needed to sustain beach nourishment into the late 21st century despite the broad uncertainty range associated with these estimates. In many of our forecasts, beach nourishment is a nearly constant activity after the 2070s and 2080s. This would pose an incredible logistical challenge that exceeds the capacity of the current dredging industry, and estimating the ecological impacts of such large scale, frequent dredging exceeds current scientific understanding. There is a need for testing novel approaches to limit beach erosion while maintaining the ecological, economic, and protective benefits that beaches provide. Early small-scale projects will help identify strategies that could eventually be implemented at large scales, potentially reducing economic and environmental costs. The coastal ocean is one of our nation's greatest resources, and strategic management is necessary to preserve this resource for generations to come.

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6 Appendices

Appendix A: Supplemental Plots

A.1 Sand demand forecast plots

Below are sand demand forecast plots for each beach analyzed in the study area. The plots show individual instances (points) as well as a spline fit to show the general trend for each forecasting scenario. Plots are presented in order from south to north.

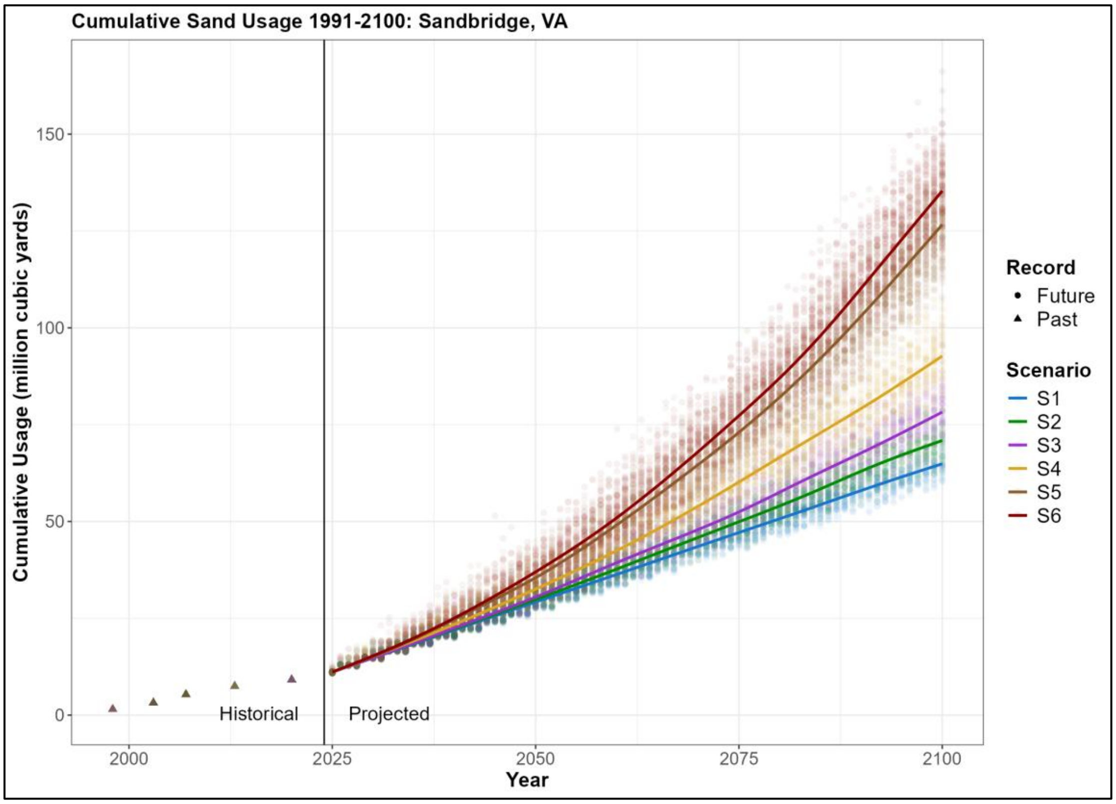

Figure A-1. Forecasted cumulative sand demand for Sandbridge, Virginia
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

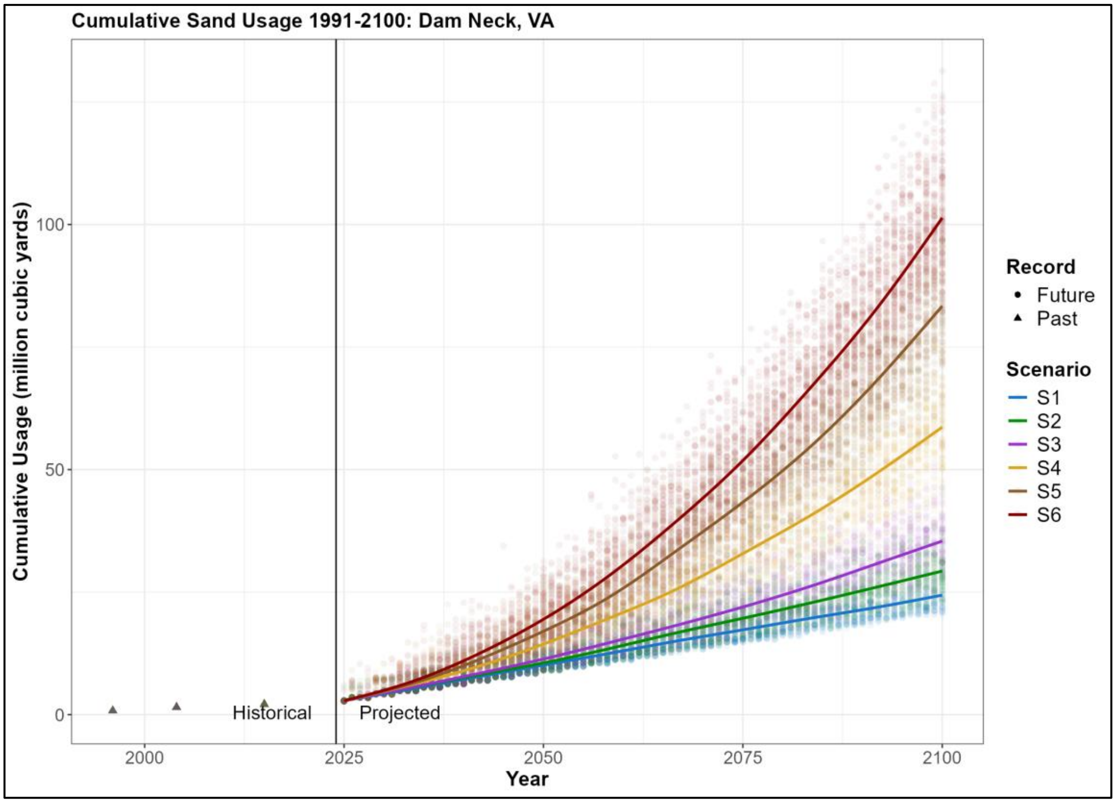

Figure A-2. Forecasted cumulative sand demand for Dam Neck, Virginia
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

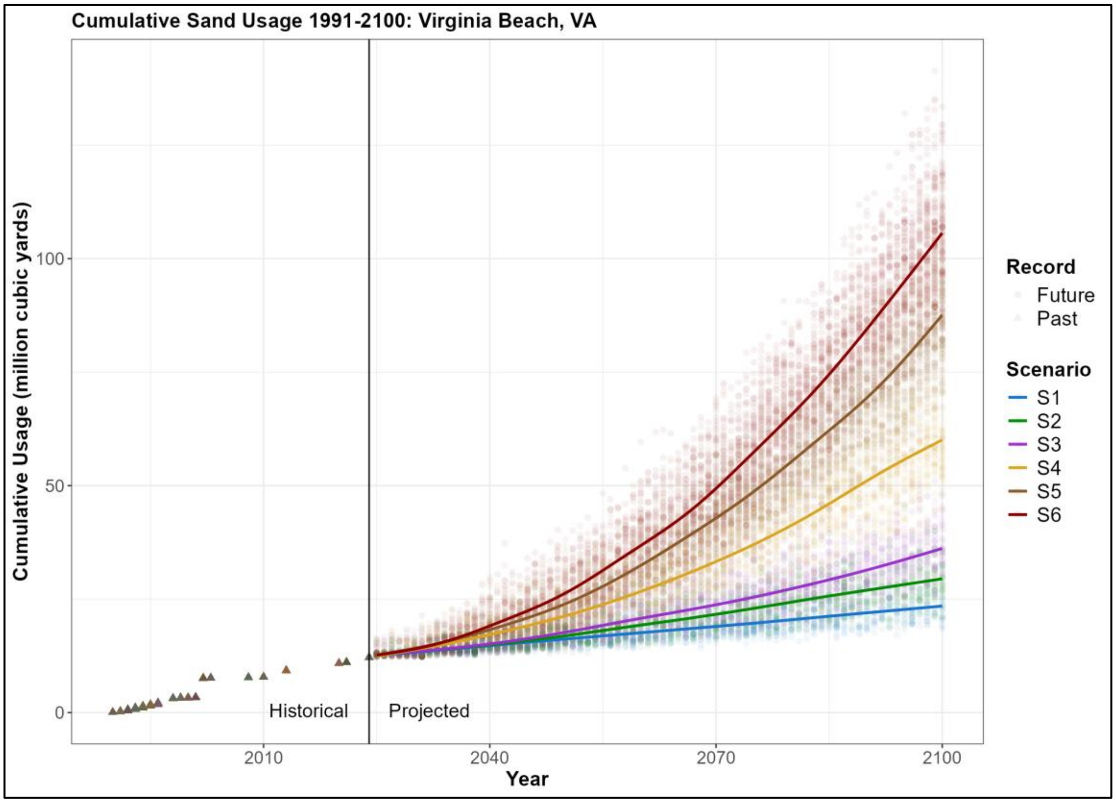

Figure A-3. Forecasted cumulative sand demand for Virginia Beach, Virginia
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

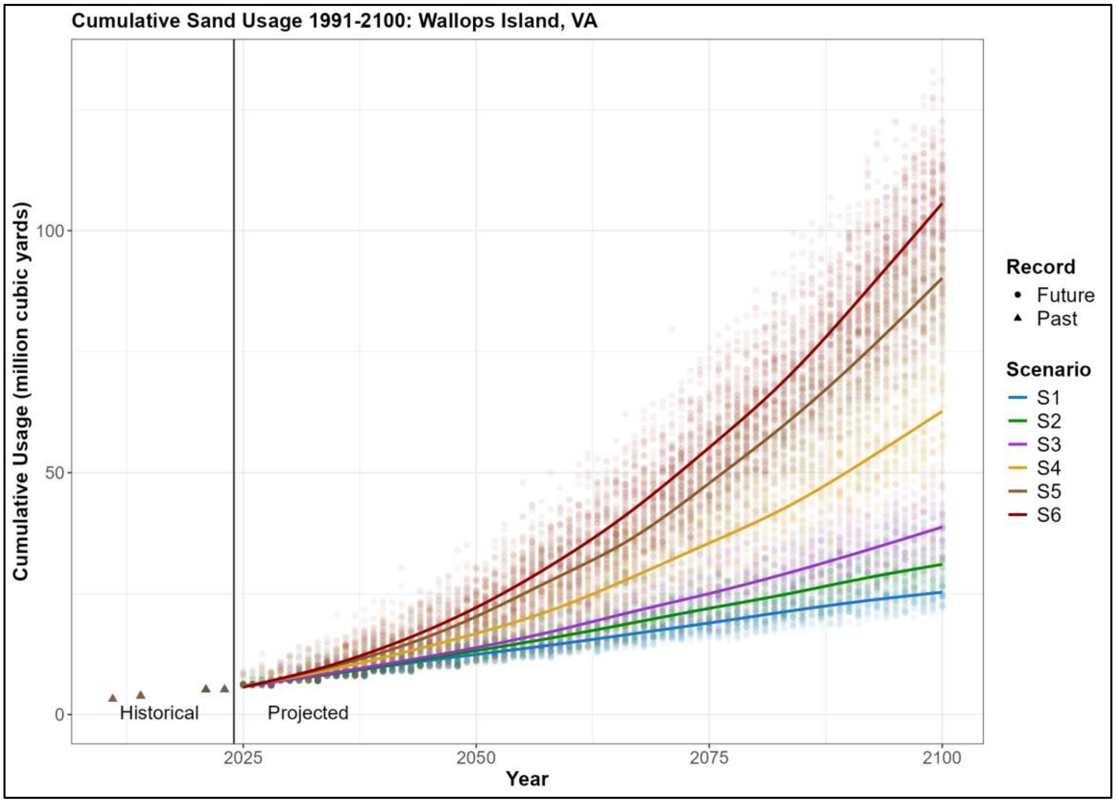

Figure A-4. Forecasted cumulative sand demand for Wallops Island, Virginia
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

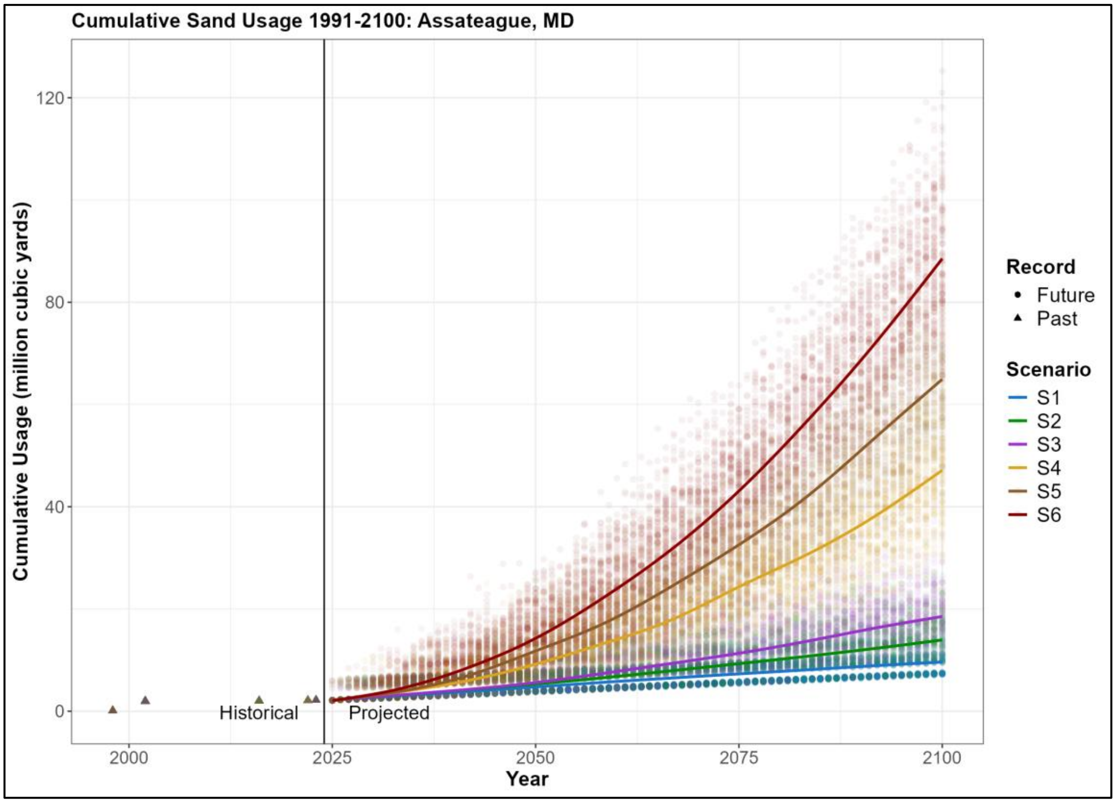

Figure A-5. Forecasted cumulative sand demand for Assateague Island, Maryland
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

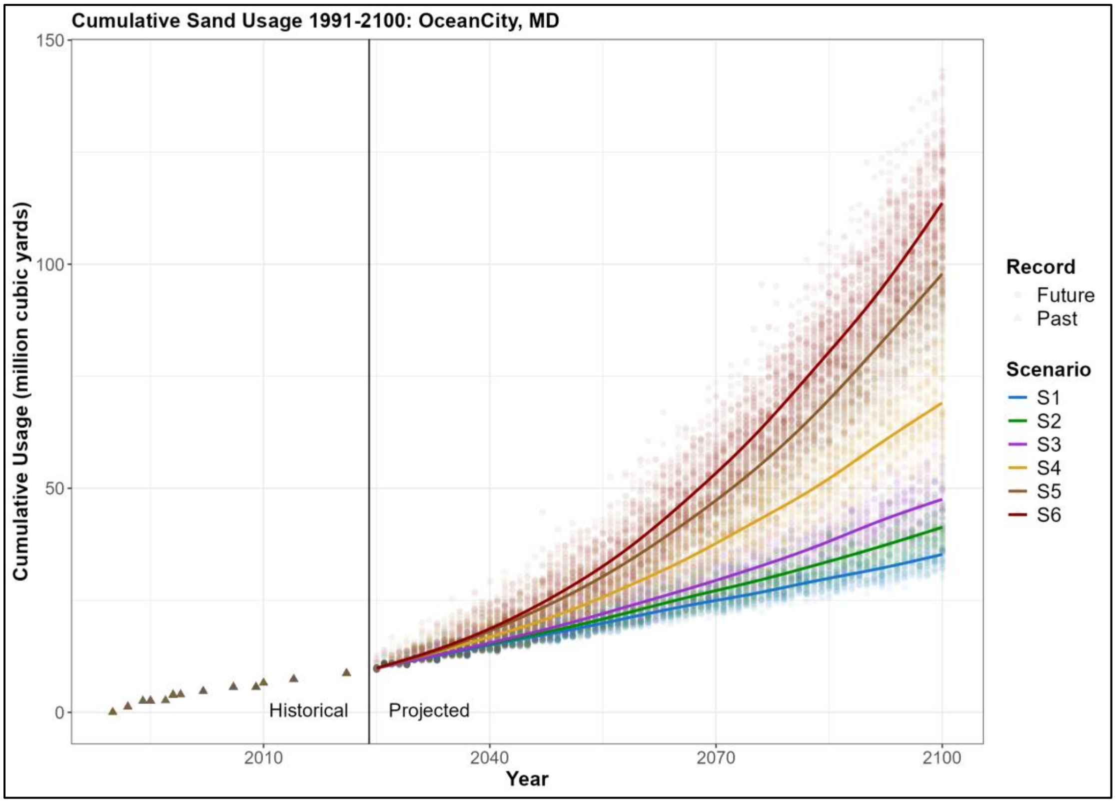

Figure A-6. Forecasted cumulative sand demand for Ocean City, Maryland
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

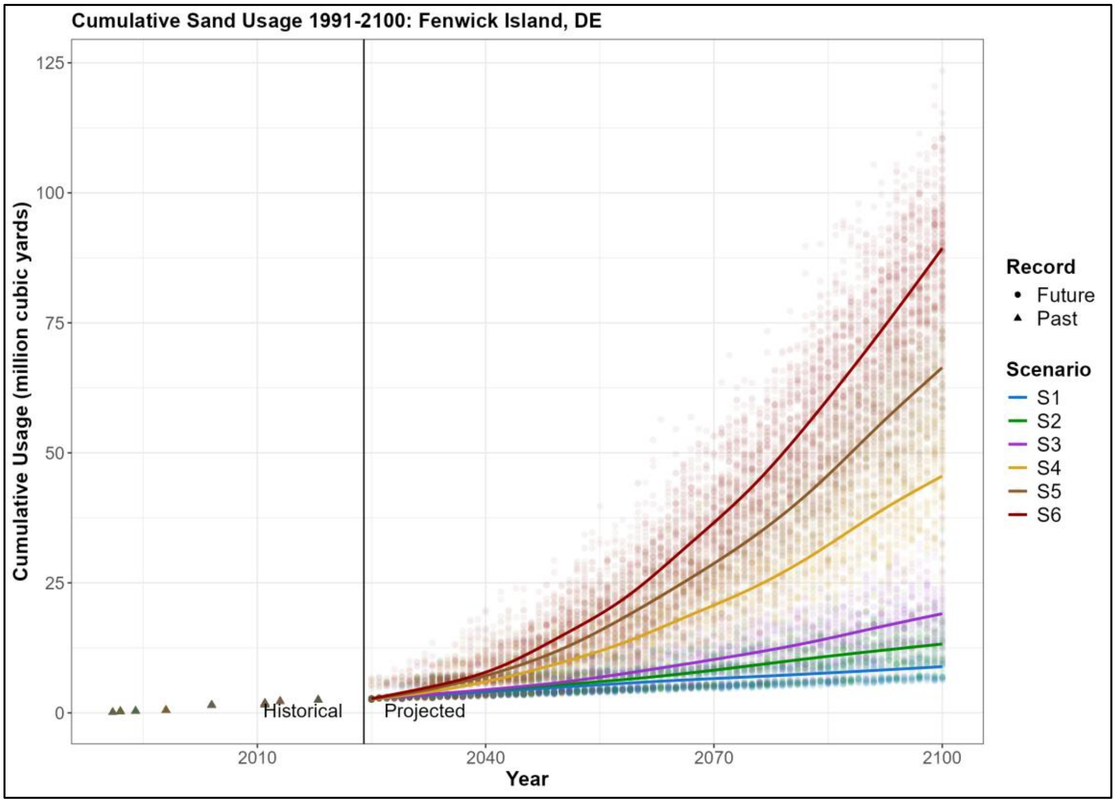

Figure A-7. Forecasted cumulative sand demand for Fenwick Island, Delaware
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

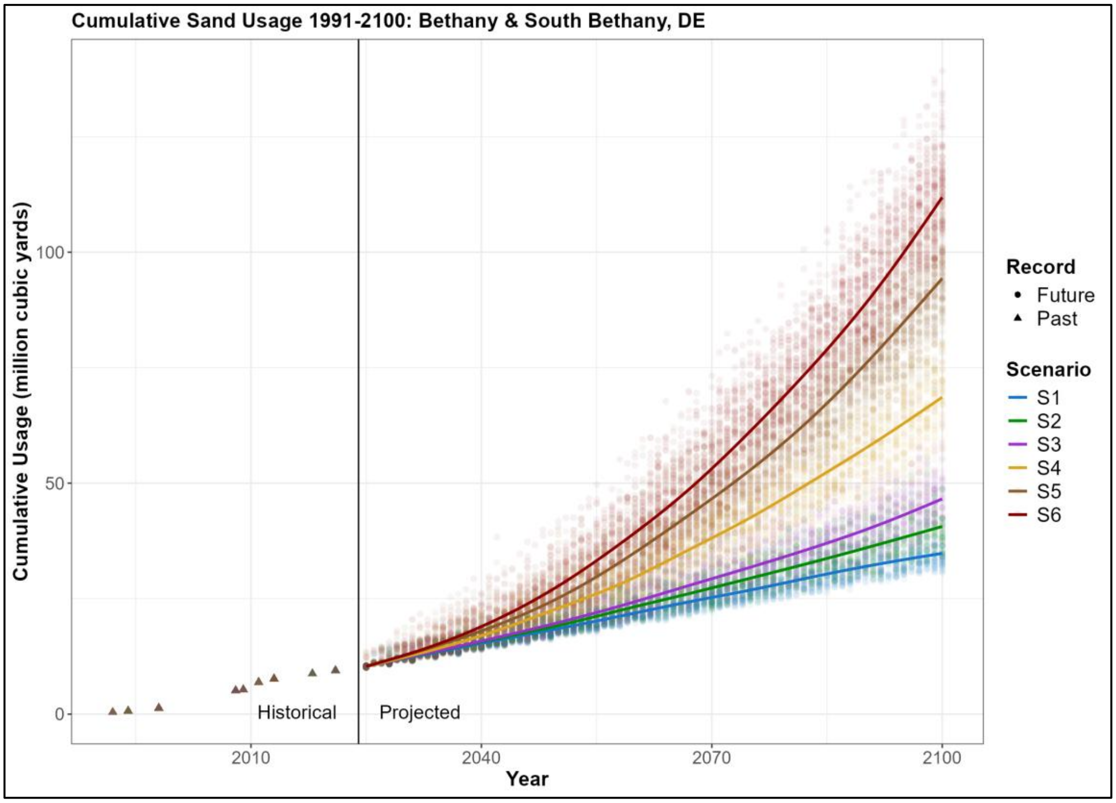

Figure A-8. Forecasted cumulative sand demand for Bethany & South Bethany, Delaware
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

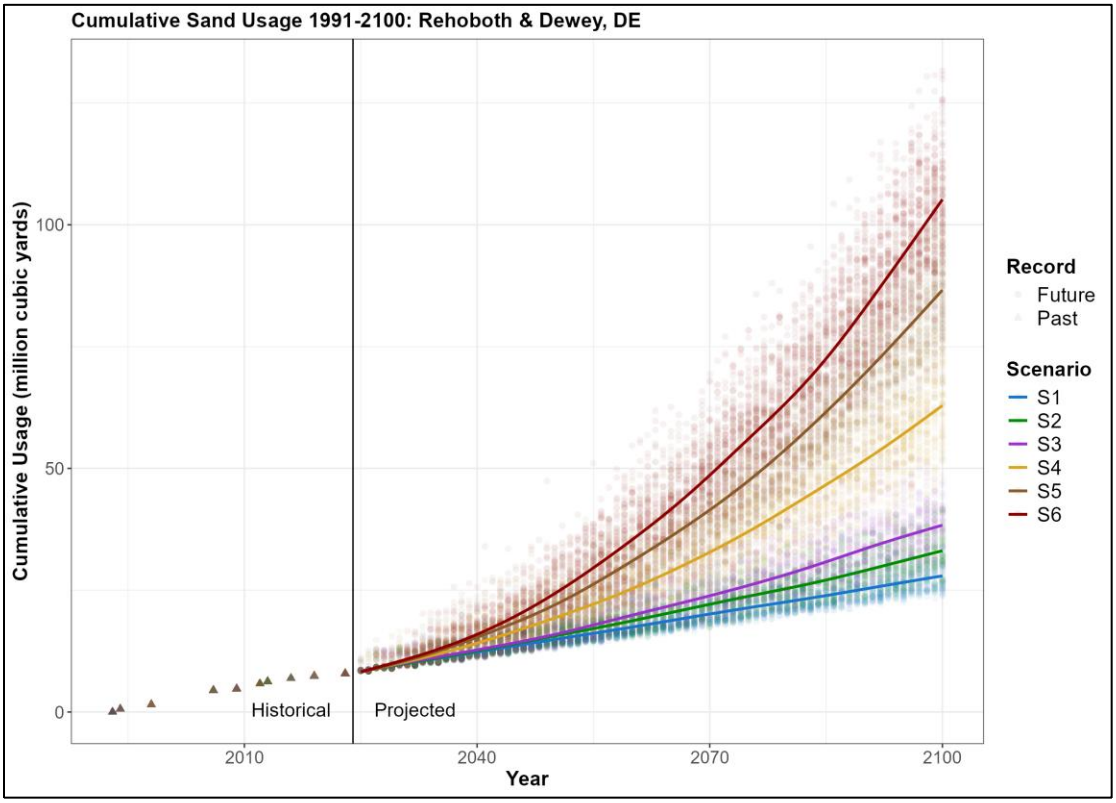

Figure A-9. Forecasted cumulative sand demand for Rehoboth & Dewey, Delaware
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

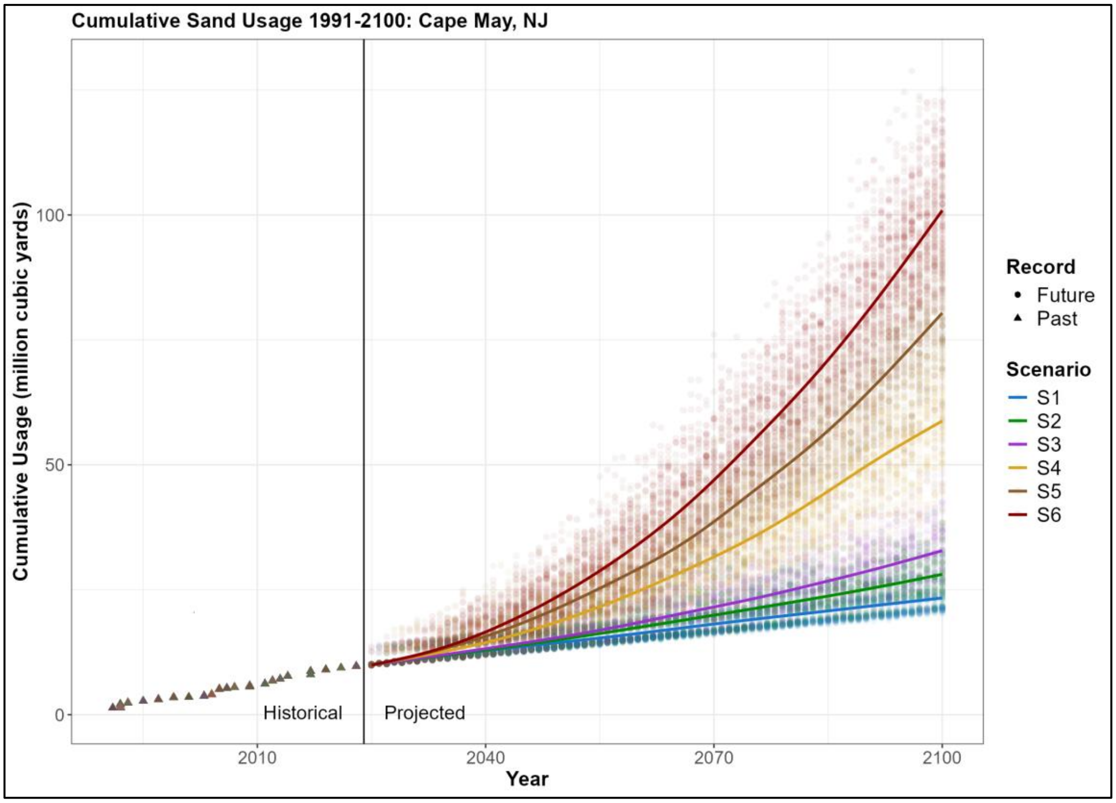

Figure A-10. Forecasted cumulative sand demand for Cape May, New Jersey
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

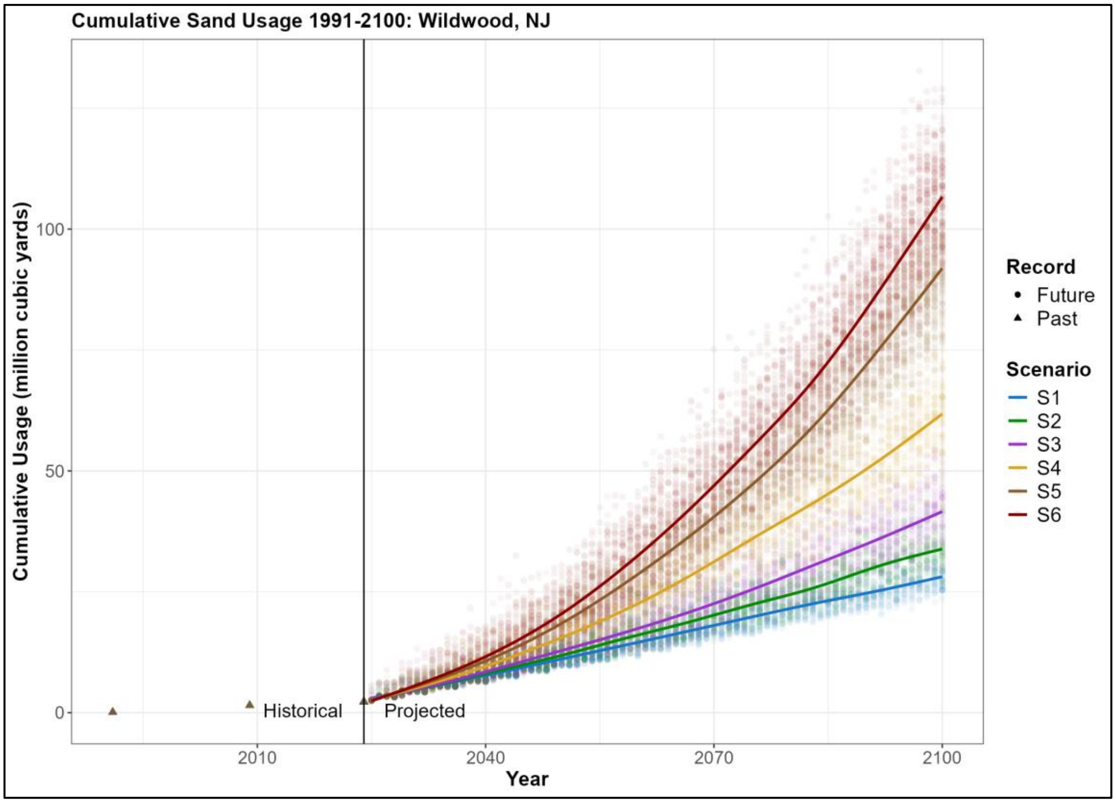

Figure A-11. Forecasted cumulative sand demand for Wildwood, New Jersey
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

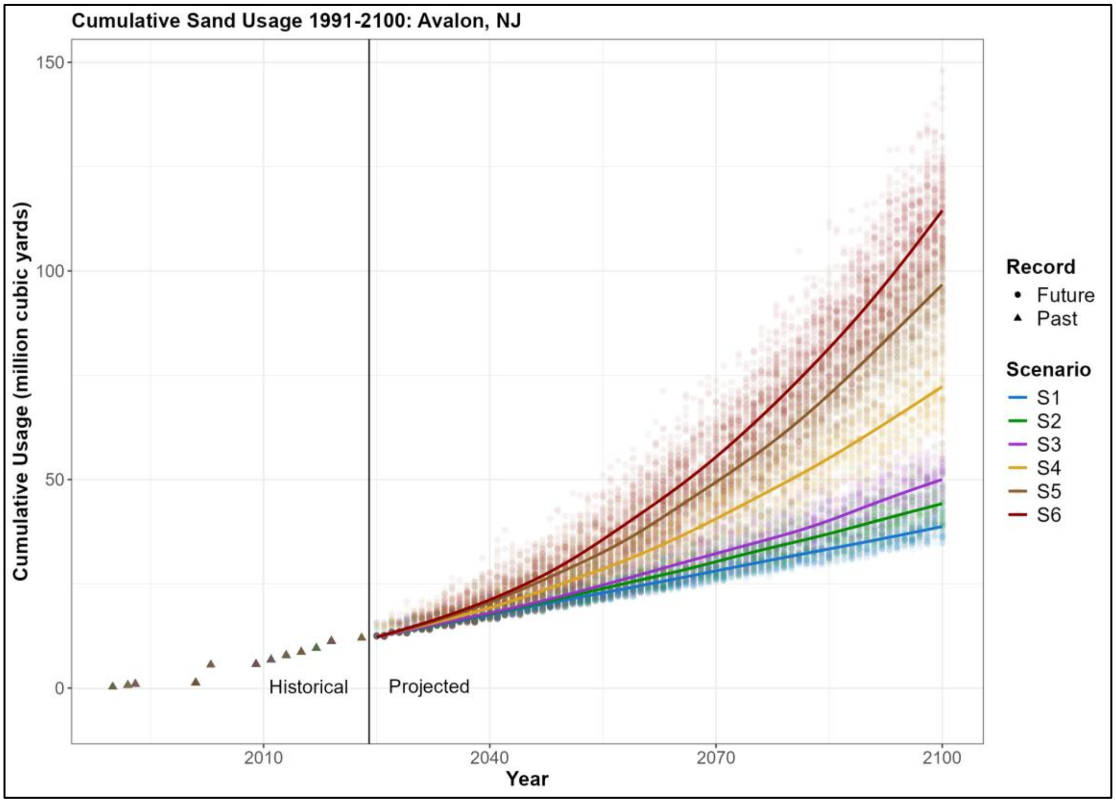

Figure A-12. Forecasted cumulative sand demand for Avalon, New Jersey
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

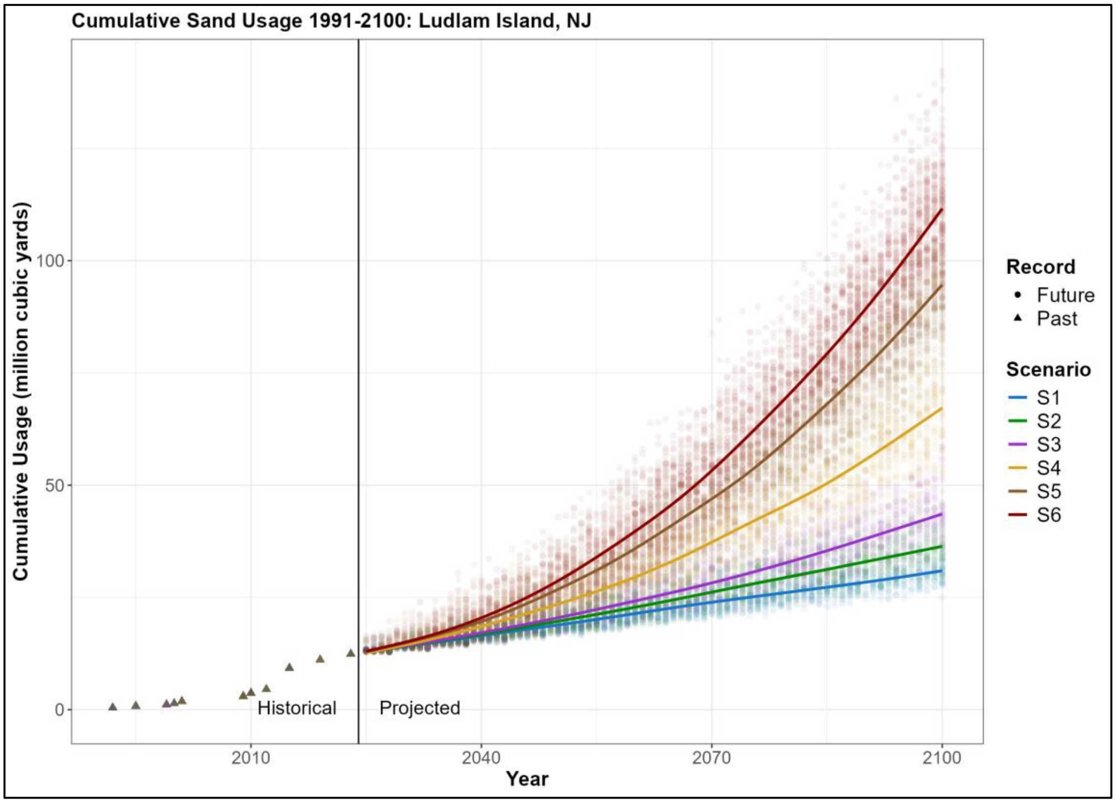

Figure A-13. Forecasted cumulative sand demand for Ludlam Island, New Jersey
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

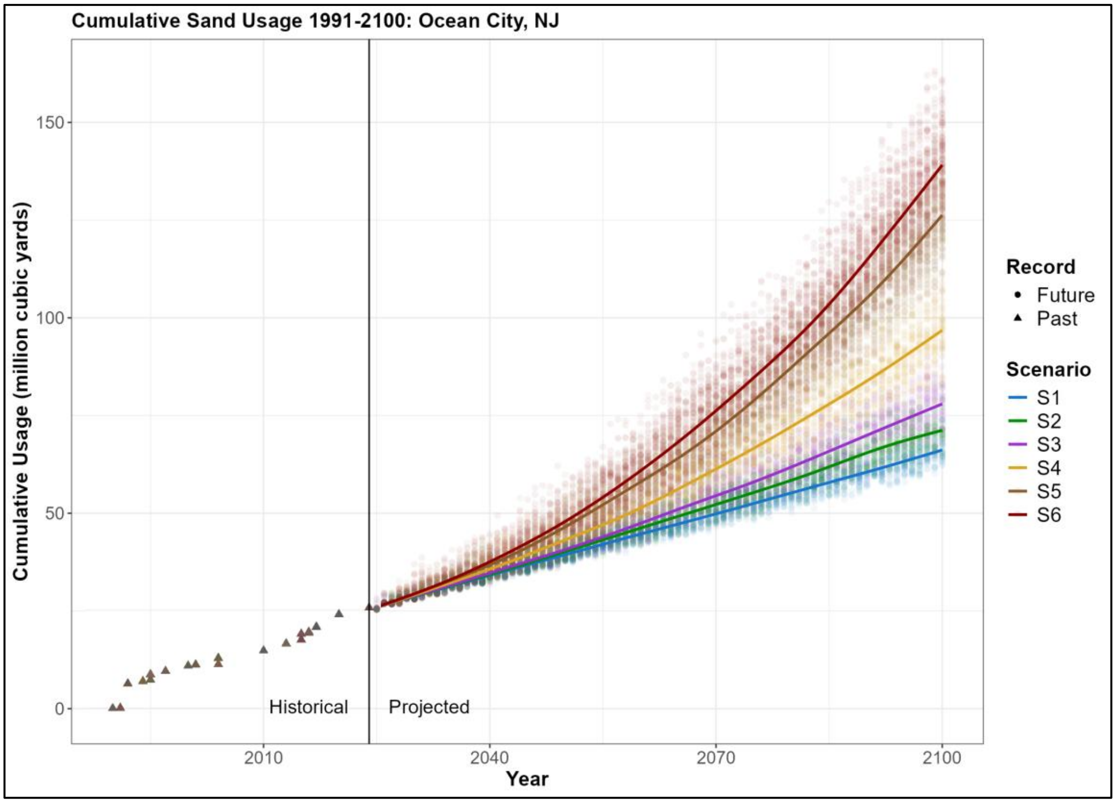

Figure A-14. Forecasted cumulative sand demand for Ocean City, New Jersey
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

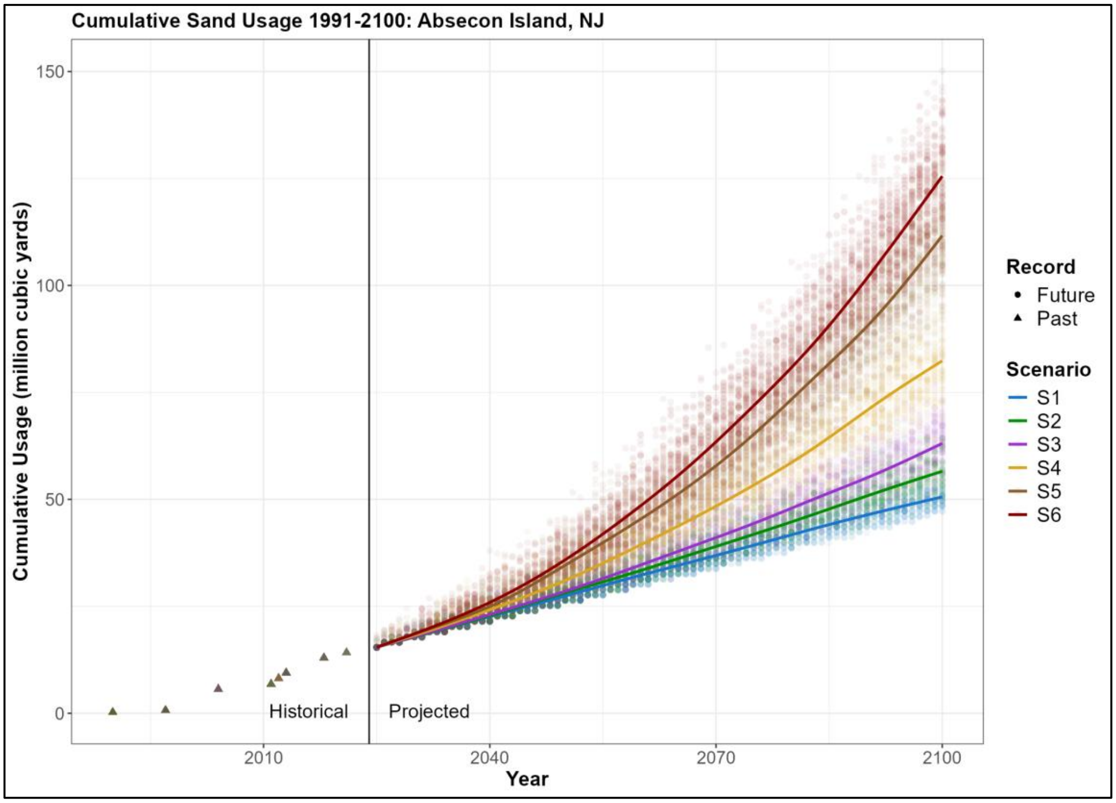

Figure A-15. Forecasted cumulative sand demand for Absecon Island, New Jersey
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

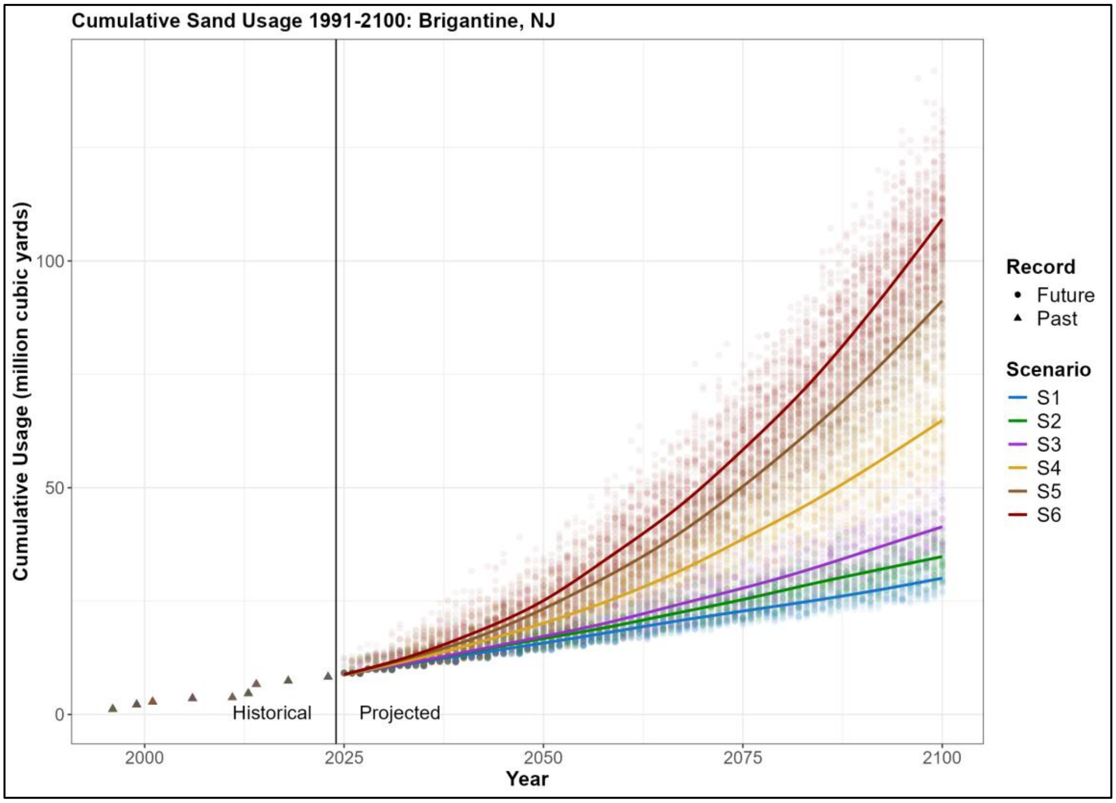

Figure A-16. Forecasted cumulative sand demand for Brigantine, New Jersey
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

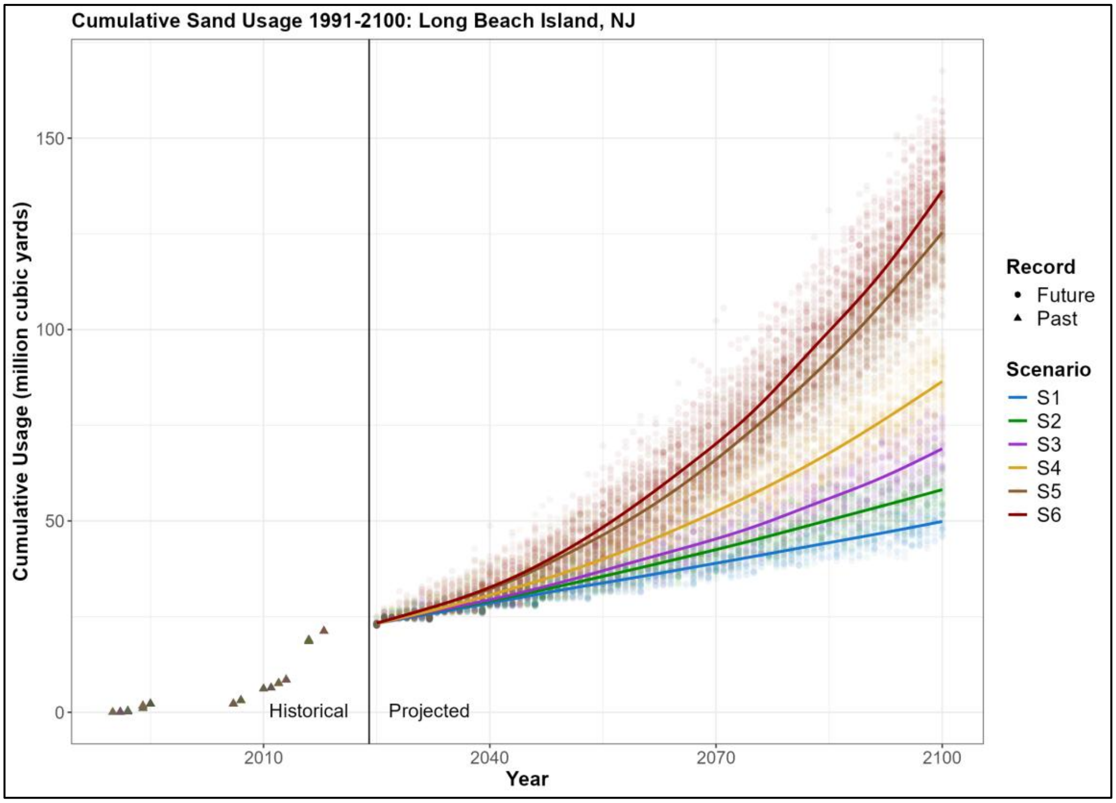

Figure A-17. Forecasted cumulative sand demand for Long Beach Island, New Jersey
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

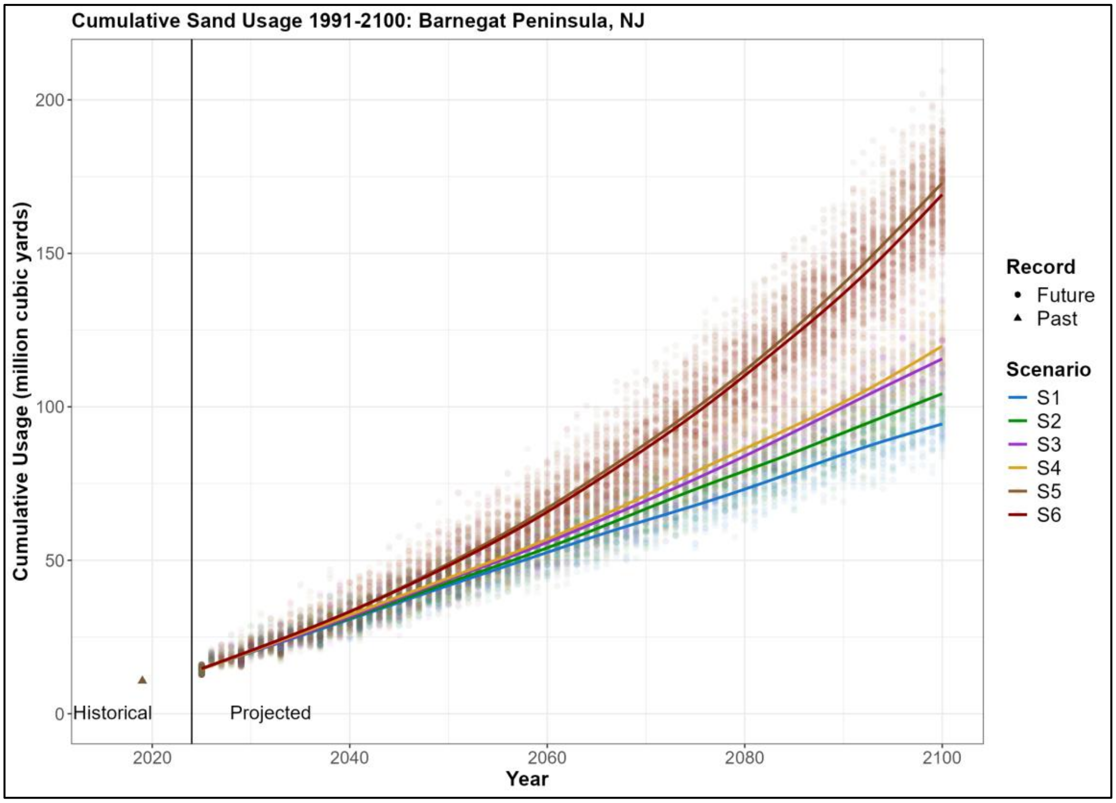

Figure A-18. Forecasted cumulative sand demand for Barnegat Peninsula, New Jersey
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

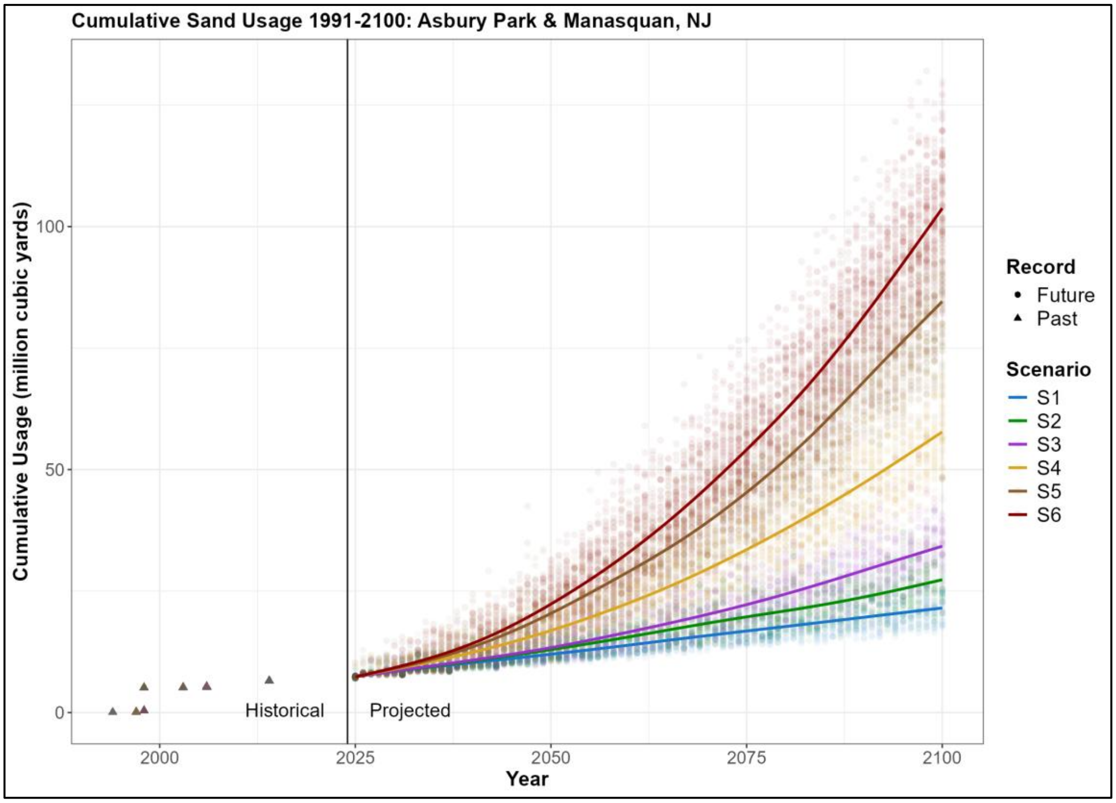

Figure A-19. Forecasted cumulative sand demand for Asbury Park & Manasquan, New Jersey
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

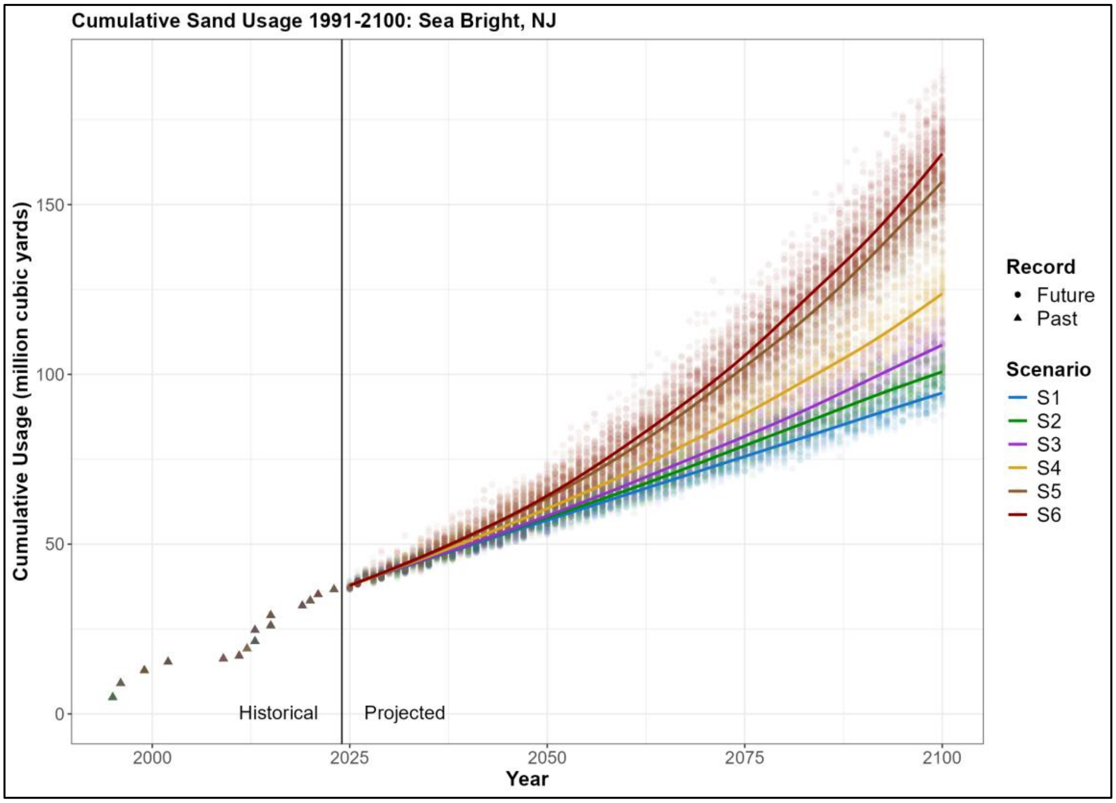

Figure A-20. Forecasted cumulative sand demand for Sea Bright, New Jersey
Different forecasting scenarios are displayed: S1 (blue), S2 (green), S3 (violet), S4 (gold), S5 (brown), S6 (red).

A.2 Spatial distribution of offshore cores

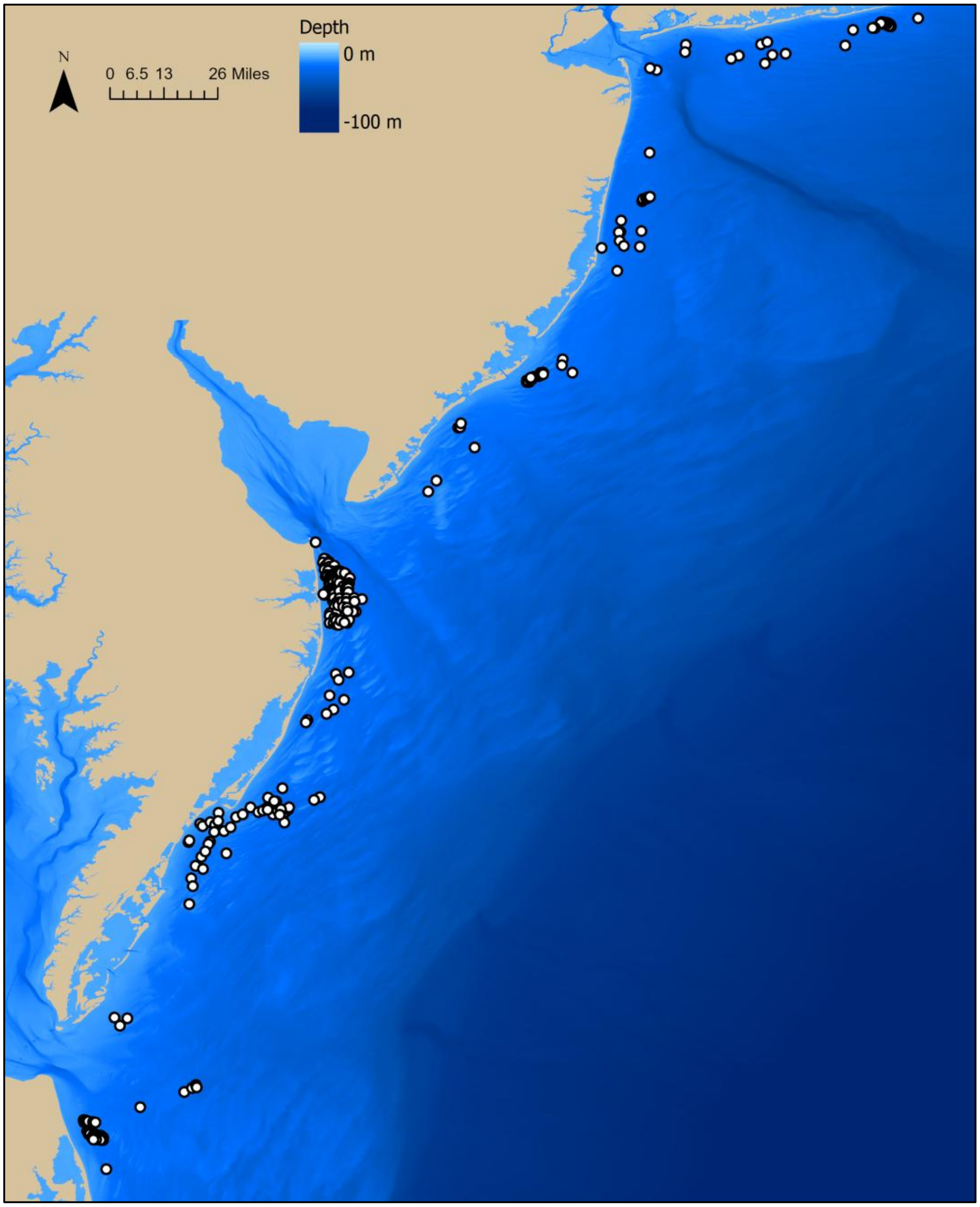

Figure A-21. Spatial distribution of 307 core samples used in sand resource quality model development

Appendix B: Notes from Mid-Atlantic Regional Sand Resources Coordination Meeting – June 4, 2025

Proceedings of the
2025 Mid-Atlantic Sand Resources Coordination Meeting

June 4, 2025
Hybrid Meeting (In-Person/Virtual)
University of Delaware
Newark, Delaware

Co-Sponsors:
Delaware Geological Survey
United States Bureau of Ocean Energy Management

Prepared under US Bureau of Ocean Energy Management
Cooperative Agreement: M23AC00014
Award Period: October 1, 2023 – June 30, 2026

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2025 Mid-Atlantic Sand Resources Coordination Meeting

Overview

The cooperative agreement M23AC00014 between the US Bureau of Ocean Energy Management (BOEM) and the Delaware Geological Survey (DGS) seeks to investigate long-term, large-scale demand and supply trends for offshore beach sand resources across the Mid-Atlantic. As part of this agreement, DGS hosted a regional coordination meeting for regional partners involved in beach nourishment and coastal sediment management. The goals of this meeting were to:

- Connect regional parties and districts involved in beach nourishment and sand resources management
- Identify challenges and data needs for long-term sand resources management in the Mid-Atlantic
- Identify opportunities for inter-state and inter-agency collaborations
- Set the groundwork for establishing a Mid-Atlantic Sand Resources Working Group

The meeting was well attended, with roughly 18 attendees in person and over 40 online. Attendees represented state geoscientists and natural resource managers from South Carolina, North Carolina, Virginia, Maryland, Delaware, New Jersey, New York, Connecticut, Massachusetts, New Hampshire, and Maine, as well as federal partners from BOEM, the US Army Corps of Engineers (USACE), the US Geological Survey (USGS), the National Ocean and Atmospheric Association (NOAA), and the National Aeronautics and Space Administration (NASA).

The meeting began with a brief introduction from Daniel Warner (DGS, Principal Investigator), followed by a broad overview presentation on recent and future plans for sand resources management on the outer continental shelf by Kerby Dobbs (BOEM, Project Officer). Other presentations ranged from state-specific beach nourishment and sand resources management projects to big-picture talks on long term trends and visions of coastal sediment management. A brief overview of each presentation is provided in this report, followed by notes taken during topic-based and open discussion periods following the presentations. The meeting began at 9:30 am and concluded around 4:15 pm EST.

I - Presentation Summaries (Presentation slides are attached at end of this document)

Overview of BOEM National Offshore Sand Inventory (NOSI) Efforts in the Mid-Atlantic
Presenter: Kerby Dobbs, BOEM

This presentation introduced BOEM's long term vision of Ideal Sediment Management, which seeks to balance multiple demands for space on the outer continental shelf, including sand resource management. The presentation then provides an update on current offshore data acquisition efforts by BOEM and its partners, including vibracore and seismic collection campaigns.

Regional Sediment Management: Opportunities and Lessons Learned from the Gulf to the Mid-Atlantic
Presenter: John Swartz, TWI

This presentation covers previous and ongoing work by The Water Institute (TWI) on regional scale sand resource management and offshore usage conflicts in the Gulf and Mid-Atlantic. The presentation explores economic, geologic, and coastal resilience aspects of offshore sand as a strategic resource, and it focuses on several specific areas of interest to illustrate these concepts.

Assessing 21st century beach sand supply and demand in the Mid-Atlantic
Presenter: Daniel Warner, DGS

This presentation provides an update on ongoing work by DGS that investigates long term forecasts of offshore beach sand demand and supply across the Mid-Atlantic. Topics include propagating uncertainty through demand forecasts, methods for refining large lithology datasets, and seafloor sediment modeling.

Offshore sand and mineral resource investigations in Virginia: Historical insights and future opportunities

Presenter: David Hawkins, VADOE

This presentation introduces an exciting opportunity for utilizing offshore sand resources both for coastal resilience projects and as a potential source of critical minerals. It provides an update on an ongoing Virginia Department of Energy (VADOE) project that investigates the feasibility of extracting critical minerals from beach sand as a means for offsetting project costs.

Delaware Coastal Regional Sediment Management (RSM) Strategies: Conceptual Practices for Primary Shoreline Management Challenges
Presenter: Joseph Faries, DNREC

This presentation details the Delaware Department of Natural Resources and Environmental Control's (DNREC) current regional sediment management activities along the state's Bayshore and Atlantic coasts. Specific focus is given to inlet ebb and flood shoals, a need for better sand resource characterization in Delaware Bay, and sand transport dynamics surrounding Cape Henlopen and the massive nearby Hen and Chicken's Shoal.

The New Jersey Sand Suitability Model
William Sulzmann, NJGWS

This presentation walks the audience through a new model developed by the New Jersey Geological and Water Survey (NJGWS) for assessing sand resource suitability. The model provides a flexible framework for identifying potentially promising sand resource units and overlaying different potential conflict layers (e.g., prime fishing areas, cable corridors, etc.) to produce a weighted spatial distribution of sand resource suitability.

The Impact of Wind Farms on Sand Resources Access
Henry Bokuniewicz, Stony Brook University

This presentation addresses spatial conflicts between sand resource extraction and other use cases, such as wind energy, both along the Long Island, NY coastline and Europe. It also introduces findings and data tools from the International Council for the Exploration of the Sea's marine sediment resources working group, providing interesting insights on offshore sand resources management from an international perspective.

Potential MA Offshore Sand Resources Areas
Todd Callaghan, MACZM

This presentation covers recent work by the Sediment and Geology working group of the Massachusetts Coastal Zone Management (MACZM) program on identifying potential offshore sand resource areas. It introduces primary data sources, along with their geologic mapping approach, and explores the avoidance criteria and characterization efforts that are used in final sand resource determinations for the state.

Marine Sand and Gravel Resources and High-Resolution Surficial Geology Mapping in the Western Gulf of Maine
Larry Ward, University of New Hampshire

This presentation covers the status of a large scale surficial geologic mapping effort for the Western Gulf of Maine seafloor, which includes both sand resources and benthic habitats. This has been a major effort consisting of a tremendous amount of data processing and collection. The presentation highlights successes and challenges for mapping the seafloor in a highly heterogeneous region.

Status of Sediment Usage for USACE North Atlantic Division Coastal Storm Risk Management Projects: New York to Virginia
Lynn Bocamazo, USACE

This presentation gives a broad overview of USACE's current and future efforts for regional sediment management for coastal resilience, navigation maintenance, and aquatic ecosystem conservation. It also provides a very useful breakdown of past beach nourishment volumes and anticipated needs for each USACE district along the North Atlantic.

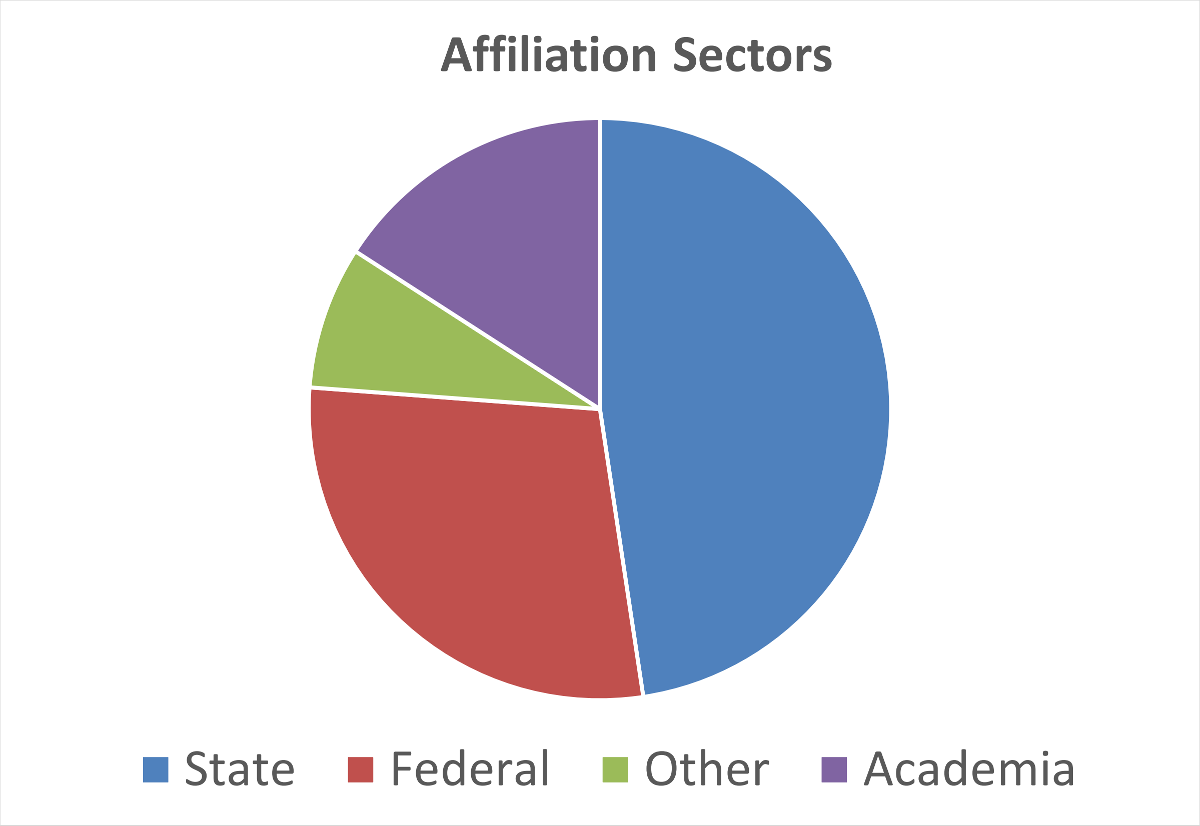
Where It's At: USGS Products that Aid in Sand Resource Identification

Laura Brothers, USGS

This presentation provides an overview of USGS's regional offshore geology studies along the Atlantic coastline, highlighting the many useful data products that have been derived from seismic and vibracore data. It also provides great illustrations on the evolution of barrier islands and shoal complexes in the Mid-Atlantics since the last glacial maximum. *Note: Several data products and methodologies are available from this work, although the final report is still in review.

II - Discussion Notes

Participant affiliations:



Total participants:
In-person - 18
Online - ~45

Notes by discussion category:

On spatial/temporal conflicts…

- Different regions treat avoidance criteria differently. Some states will immediately remove a resource from consideration if there is recreational fishing, others will just count it as a strike against. This lack of consistency can cause confusion among stakeholders. In Long Island for example, recreational fishing seasons reduce dredging windows to only ~3 months/yr in some places. Bottom habitat is the biggest concern.

- Similar situation in NJ, especially in inlets and areas of anadromous fish habitat, and DE Bay shore communities. The dredging season is reduced to 3-5 months in these areas. One issue in NJ is that conflicts from "prime fishing areas" are effectively everywhere because the ruling vaguely says, "prime fishing areas and areas that are similar to prime fishing areas". This puts a big constraint on expanding/searching for sand resources, and it emphasizes the need for clear language.

- We need to learn from more mature management frameworks: The European Union (EU) has a well-established offshore management framework for spatial planning and resource management.

On local erosion/shoreline loss trends…

- In Delaware, it is noted that several consecutive days of northeasterly winds often can result in significant erosion even without a major storm.

- Similarly, small variations in prevailing wind patterns can cause consistently elevated tide ranges for weeks or months that have caused a lot of erosion, even though you may not notice the changes in wind if you live there.

- The Norfolk area has had many issues with sunny day flooding (not necessarily beach erosion per se) and there is a big push to address this with blue/green infrastructure.

- Maine has seen an increase in the intensity of storms from the southeast, while the system has historically acclimated to nor'easters. This has caused several instances of major erosion in normally stable areas, prompting calls for nourishment.

- A question was raised regarding testing different construction/design strategies, or paired strategies (e.g., high slope beach + breakwater) that could limit sand loss. But, ultimately it is a question of costs-v-benefits, and currently just using sand is generally the cheapest option (it is still quite expensive).

- Safety is also a concern - we don't want to create rip currents or dangerous wave conditions even if that means reduced erosion.

- Event sequencing is an area of increasing interest that also dictates erosion. A beach can only take so many hits. One hit may cause an enhanced erosive effect from a subsequent small event. Example: TX gulf shore was hit by hurricane > weakens shore defense. Then, a relatively small event caused massive breaching/overwash before the system recovered. It would be great to understand this better. But, such series of events are very hard to predict, so getting data over the course of the series is quite difficult.

- Hotspots remain an area of concern, especially in NJ. Hoping for more opportunities to study causes and potential solutions.

On finding new sand resources…

- Issue in federal waters: USACE needs a signed chief's report (hard to get) in order to be able to deny a company from laying a cable, footing, etc. across a potential sand resource. USACE can ask nicely for a company to avoid potential resources, but they cannot enforce it without a lot of proof and official stamp.

- Sand resources not in traditional shoal structures:
    - **Sand-filled paleochannels**: there were some ASAP cores taken in these, many were muddy. The fill content is variable from channel to channel, so it isn't a reliable approach for finding sand.
    - **Sheet sands**: Difficult to parse, as they lack a lot of bathymetric definition, but they are a potential source. Louisiana has low relief sand borrow areas and has been using them due to lack of clear shoals. Tradeoffs are present in this landscape. Shoals are also clearly a more desirable habitat. Sheet sands and flatbed sands lack the structure to make them high quality habitat and may have less ecological conflict as a sand resource. However, they are harder to find. A similar concept probably applies to sand-filled paleochannels. Not all have sand, but they also are not highly desirable conservation targets.

- For decades we have adhered to the idea that if one place has one value, you should just look elsewhere. Dredging is so limited spatially and this increases costs. Cutoffs on fishing grounds etc. ignore the facts that there could be a win-win for multiple groups. We need to investigate balance between multiple use cases. We may be able avoid simply excluding areas based on a polygon on a map. Need to better define alternatives and tradeoffs. Esp as we look further offshore. Call it "adaptive management" - strategies that allow for access but with strategies that minimize habitat impacts.
    - This is true and there are definite benefits, but keeping multiple potential sources on the table is more effort and requires more assessments. It is a big potential loss of money and effort to scout a resource only to use it one time.

- Regarding the recent focus on glass recycling or enhanced rock weathering applications of material to meet sand demand. Some work, but no projects of sufficient size to remove significant amounts of carbon. Pilot studies are ongoing in NC and NY (https://www.vesta.earth/field-pilots). It is noted that BOEM has no jurisdiction in state waters and that any sediment placed on the OCS would be regulated by the EPA. However, it is likely that we can generate insights by tracking the fate of any olivine sand placed in the nearshore to potentially optimize design and placement of coastal nourishment projects.

On public sentiment/outreach/interaction…

- People think beach nourishment is easy. That is a big hurdle. They don't understand how much work goes into identifying sand resources. Similarly, the public often doesn't recognize the problem until it is right there, and/or assume that sand is everywhere and easy to access. Otherwise, it is viewed as a "rich people" problem, so they brush it off as it doesn't affect them.

- Public doesn't always trust the science (or thinks any govt communication is politically motivated) and asks "Why did you do it like that?" after the fact. Anecdote - patching a soon-to-breach barrier island in Delaware caused people to get upset because there was insufficient awareness of coastal processes, but it would've been a much bigger deal if the breach had occurred. Similarly, there are shifting baselines on public sentiment. It used to be - nourish to avoid direct property damage, it is now - our beaches must be perfect all the time. Permitting can also take a lot of time, and that does not necessarily progress with state-of-the-art science.

- Public sentiment varies over time. Bad winter storms in 2023/24 led to a lot of news coverage of beach erosion in Long Island, which then caused a flood of requests for nourishments that were not consistent with historical trends.

- USACE public affairs office has increasingly pushed for public awareness. Getting it out is possible, but getting traction/engagement is still a challenge. The percentage of nourished beaches in NJ has nearly doubled since Sandy, which has led to wider public awareness. There are links to corps projects on NJ and town websites, which helps. However, people are stretched thin, and getting teams on the ground to engage the public is very tough. Public meetings are time-consuming and often after hours, but they probably are the best way to connect (there will always be negative feedback).

- Having good reporters that you trust is key for getting messages out. A good reporter will get the info out clearly in a way that is digestible to the public. However, academia is easier to do this, since there are fewer communication barriers than an official government release.

- Environmental literacy is relatively low in general. What is a barrier island? Why do beaches move? Outreach on beach ecology/geomorphology would be great. There is poor integration of these things in K-12 curricula. Finding good science writers in your agency can really help.

Similarly, a lot of beach community residents are transplants who do not have background knowledge of major storms or coastal processes. This is a big educational hurdle.

- Anecdote- A Maine county has purchased its own small dredge just to maintain channels and then do BUDM projects communities. But now they are looking to take non-BUDM sources to communities. Very little communication/overpromising leads to: Communities assume that they can get material from anywhere at any time.

- Building a story/narrative to engage public is key. Short format media can be very helpful, although it is a daunting place to enter. Coming from an economic angle can also help. Bonds may be better rated in towns with proven resilience strategies/efforts, which is a huge plus for coastal communities.

On future meetings…

- The Mid-Atlantic Regional Council on the Ocean (MARCO) is in the process of starting up a seafloor working group that could be a good venue for these types of meetings/discussions in the future.

On data needs…

- Robust pre- and post-storm surveys would be very useful for studying trends in erosion. Parameterize the whole event to try to draw patterns over time, establish effects on characteristic shape. A good argument for periodic drone surveys and newer applications of satellite-based SAR.

- Improving data sharing with wind energy developers, especially since many of them are pulling back. This could be an opportunity to get a lot of new geotechnical data. BUT wind energy developers are looking for good footings and routes for cables, which is not necessarily consistent with sand resources. These efforts have had mixed success.

- Budget cuts mean that field work will be diminished, but it opens opportunities for reanalysis of legacy datasets and leveraging of things that already exist. A lot of big expensive projects have been funded by earmarks and one-time appropriations (studying the ocean is very, very expensive) rather than consistent programs.

- Enhanced resource data for early planning. We need information to back up bargaining/negotiation efforts with other offshore use cases. Financial impacts are not just for sand, but also costs needed to find new sand whenever a source is taken off the table. These types of economic analyses are lagging.

- Soon-to-be-published (in review at Geosphere) journal article (*Paleodrainage Controls on Shelf Evolution in a Mid-Latitude Passive Margin: A synthesis*) has an appendix (PDF slide deck) compiled from existing publications reconciling chirp subbottom, core, and geochronology data in Delmarva**.** Reach out to Laura Brothers (USGS) if you want a pre-print of this document.