Assessing 21st Century Offshore Beach Sand Supply and Demand in Delaware and Maryland

November 2023

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Prepared under BOEM Cooperative Agreement M22A00001
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CITATION

Warner DL, Ramsey KW, Wunsch DR (Delaware Geological Survey, Newark, DE). 2023. Assessing 21st century offshore beach sand supply and demand in Delaware and Maryland. Sterling VA: U.S. Department of the Interior, Bureau of Ocean Energy Management. Agreement No.: M22AC00001.

ACKNOWLEDGMENTS

The following BOEM offices or programs contributed to this document: Marine Minerals Program. We also acknowledge professional guidance, feedback, and data support from the US Army Corps of Engineers Philadelphia and Baltimore Districts, the Maryland Geological Survey, the Delaware Department of Natural Resources and Environmental Control.

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List of Abbreviations and Acronyms

ASBPA	American Shore and Beach Protection Association
BOEM	Bureau of Ocean Energy Management
BUDM	Beneficial Use of Dredge Materials
cy	cubic yard
DGS	Delaware Geological Survey
DQM	Dredging Quality Management
MEC/UXO	Munitions of explosive concern/Unexploded ordnance
OCS	Outer Continental Shelf
RSLR	Relative Sea Level Rise
SP	State Park
USACE	US Army Corps of Engineers

2 Introduction

The Atlantic-facing beaches of Delaware and Maryland are major regional economic drivers through tourism, recreation, and commercial enterprises (Latham and Lewis 2012). Maintaining the structure of these beaches protects coastal infrastructure, preserves their economic and aesthetic value, and maintains habitat for dune and beach nesting species. Historically, when major storms would occasionally erode large swaths of beach they would receive sand nourishments, where sand is dredged from the seafloor and pumped onto the shore, to restore their structure. However, the DE-MD Atlantic coastline is subjected to a relatively high rate of relative sea level rise (RSLR) due to the compounding effects of land subsidence and global sea level rise, with estimated local rates of RSLR ranging from roughly 3.5 to 5.5 mm yr^{-1} (Callahan et al. 2017). Climate change projections suggest that as sea level rises, so will the frequency of erosive storm surges that wash out beaches and backing dune systems. This has necessitated more frequent beach nourishment activities in recent years, and, consequently, greater volumes of offshore sand needed to meet demand. This frequency is likely to increase over the remainder of the 21st century.

Offshore sand deposits are relatively stable compared to nearshore environments as they are exposed to less erosive energy. As a result, sand dredged from offshore "borrow areas" is generally considered to be a non-renewable resource as the sand deposits form on geologic timescales (more information on the offshore geology of Delaware and Maryland is available in Section 3.1). This means that a given sand resource can be effectively exhausted of beach quality sand, and new sand resources must then be tapped to meet demand. As easily-accessible sand resources are exhausted, resources that sit further from shore, that overlap important marine habitats, or occupy hazardous, rugged, and/or deep seafloor settings may be necessary. This can lead to increased economic, environmental, ecological, and social costs. Thus, the future of beach nourishment as a coastal protection and stabilization strategy is uncertain at both local and regional scales, as its relative costs and benefits may vary over time and across communities (de Schipper et al. 2021).

Though beach nourishment is generally considered to be a more environmentally and economically friendly option for shoreline stabilization compared to seawalls and other armoring structures, it comes with substantial concerns regarding its environmental impacts and long-term feasibility (Daniel 2011, Staudt et al. 2021). Dredging hundreds of thousands of cubic yards of offshore sand and placing this sand on the beach represents a major ecological disturbance to both the benthic community on the seafloor and beach habitat. The placement of sand has immediate ecological impacts, as thick sand layers may suffocate burrowing beach organisms. Longer term ecological impacts on beach-nesting species can occur due to differences between the characteristics of placed sand and native sand (e.g., color and texture) and differences in the slope and structure of the nourished beach (Goforth and Carthy 2022, Staudt et al. 2021). However, beach nourishment preserves the structure of the beach habitat better than hard infrastructure like groins and seawalls, as it allows organisms to access both the beach face and backing dune systems without physical barriers.

Practices have been adopted to lessen some of the environmental impacts of beach nourishments. Early beach nourishment projects would dredge deeply over a small area, resulting in localized "dead zone" pits that would accumulate fine sediments and deplete dissolved oxygen. This practice was replaced by thin (generally <10 feet) dredging to avoid major structural changes to the seafloor and allow for a more rapid return to normal sediment status and recovery of the benthic community (Staudt et al. 2021). Targeting borrow areas with relatively low biological density and timing beach nourishment projects to avoid nesting and breeding seasons of benthic and beach organisms can also reduce ecological disturbance. However, ecological impacts at dredging sites remain substantial and largely understudied. It is likely that impacts vary spatially due to differences in sediment composition and biological community structure, so environmental protection strategies must be tailored to each project area.

The pressing needs for coastline stabilization and infrastructure protection also come at a time of increasing demand for space on the OCS from a variety of different sectors. Lease areas for wind energy installations are already rapidly expanding along the Mid-Atlantic OCS. Beyond this, expansion of offshore communications cable networks, potential offshore carbon sequestration projects, and investigations of offshore critical mineral resources may all drive increased competition for OCS space in the coming century. Early planning is critical for future management of OCS resources to avoid resource conflicts, environmental degradations, and resource sterilization. This is especially true in the Mid-Atlantic and Northeastern United States, where states tend to be smaller and share thinner stretches of coastline than Southeastern, Gulf, and West Coast states. This density provides ample opportunities for interstate collaboration but also for conflicts and overlapping interests on OCS resources. The Bureau of Ocean Energy Management (BOEM) has recognized these potential issues and is taking early action to support long-term OCS management strategies to avoid such conflicts.

This project report details an investigation into historical and forecasted future demand for and supply of offshore beach sand along the Atlantic coasts of Delaware and Maryland. The key goals of this project were to:

- Forecast sand needs: We aimed to establish a baseline of past sand resource needs based on historical beach nourishment data and forecast sand resource needs into the future under different scenarios reflecting potential climate change-driven increases in high impact storm surges.

- Estimate sand supply: We aimed to estimate when current sand borrow areas may become exhausted, prompting a need for new sand sources.

- Identify potential additional sand resources: We aimed to identify possible future sand resource areas to prioritize for further sediment characterization and reserve from other potential competing interests on the OCS.

3 Study Area and Methodology

3.1 Study area

The DE-MD Atlantic coastline contains several state parks (Cape Henlopen SP, Delaware Seashore SP, Fenwick Island SP, and Assateague SP), a national seashore (Assateague), and several highly urbanized beach communities (from south to north: Ocean City, MD, Fenwick Island, DE, Bethany/South Bethany Beach, DE, and Rehoboth/Dewey Beach, DE). Much of this analysis focuses on these four major beach communities as they have used, and are forecasted to need, far more sand to meet their coastal stabilization goals than the other stretches of coastline in the study area. Rehoboth/Dewey Beach and Bethany/South Bethany Beach were grouped in this analysis despite being distinct municipalities. This was done because of the close proximity of these communities and a recent trend of simultaneous nourishment to reduce costs.

Research suggests that much of the coastline within our region of interest is actively eroding, though the northernmost (Cape Henlopen, DE) and southernmost (Tom's Cove, Assateague Island, VA) areas are actively accreting sand (Hapke et al. 2011). Localized rates of high erosion and accretion are also observed north of the Indian River Inlet in Delaware and south of the Ocean City Inlet in Maryland, which has prompted frequent beneficial use of dredge materials (BUDM) activities at their outlet shoals and inlet/harbor channels, as well as a sand bypass project at Indian River Inlet. Long stretches of state- and federally-managed beaches are found on Assateague National Seashore, MD, Assateague SP, MD, Fenwick Island SP, DE, and Delaware Seashore SP, DE. These areas do not receive regular direct nourishments and rely on sand transported by longshore drift from nourishment activities near the two inlets or periodic nourishments of major beaches. Prevailing longshore currents in the study area diverge near Bethany Beach, Delaware, with sand transported north-to-south south of Bethany Beach and south-to-north to the north (Fig 3-1).

Offshore sediment compositions in this region are the result of cyclic sea-level oscillations during the mid-to-late Pleistocene. Low sea-level periods left the shelf exposed and Atlantic-bound fluvial systems were entrenched within valleys. High relief strongly influenced coastal evolution during periods of sea-level rise, as depositional dynamics and the resulting sedimentary architectures were influenced by the irregular distribution of sediment accommodation space (Belknap and Kraft 1985). Estuarine deposits dating to several Pleistocene sea-level highstand periods are preserved within former erosional topographies while valleys incised during the most recent (late Pleistocene) glacio-eustatic cycle contain a fill record documenting Holocene sea-level rise (Kraft 1971; Belknap and Kraft 1981, 1985; Belknap et al. 1994). Valleys are incised into late Tertiary to early Pleistocene fluvio-deltaic sediments, which underlie the entire inner shelf region and crop out along paleo-valley interfluves in absence of younger sediment cover. Recent shelf sand deposits that are, in large part, winnowed from the late Tertiary outcrops, occur as distinct shoal bodies, sheet sands, and other geomorphic configurations. While dominating the surface cover by aerial extent (~70% off the coast of Delaware; Mattheus et al. 2020), they are thin to absent across portions of the shelf, and locally interfinger with muddier deposits in low-energy regions, particularly in the lee of the Hen and Chickens Shoal towards the northern end of the study area (Fig 3-1).

Sands become increasingly fine with distance offshore, beginning as coarse sand to gravel in the surf zone to very fine silty sands offshore found in thin deposits, usually less than 2 ft in thickness. The texture of nearshore sediments is related to texture of underlying deposits from which they are reworked. Deposits are fine and silty off the Pleistocene headland at Rehoboth Beach and are fine to coarse sand off the barrier south of Dewey Beach. Besides the Han and Chickens shoal, there are no large, distinct shoal structures near Rehoboth and Dewey Beach. Nearshore deposits consist of fine silty sand north of Bethany Beach and grade into fine to coarse sand with shells reworked from the underlying Sinepuxent Formation off Bethany Beach. South of Bethany Beach, nearshore deposits range from medium to coarse sand. Moving further south and offshore (>2 miles) large shoal structures begin to appear off Fenwick Island and Ocean City. These include the relatively large and well-studied Fenwick, Weaver, and Isle of Wight Shoals (Fig 3-1).

Human activities have also impacted the accessibility of offshore sand resources. An ever-present complication of offshore dredging for sand resources in the region is the presence of munitions of explosive concern (MEC), also sometimes called unexploded ordnance (UXO), along much of the coastline north of Ocean City. During World War II, artillery batteries were installed north of Rehoboth Beach and near Bethany Beach for coastal defense. These batteries conducted regular training exercises that led to wide cones of potential MEC/UXO contamination, and MEC/UXO have been found by fishermen and dredges in the past. There is also an area off Cape Henlopen that may contain relict sea mines. For the safety of dredge operators and the public, screening protocols are used on dredge heads to exclude objects large enough to be MEC/UXO. However, obvious safety concerns remain in these areas, and the potential presence of MEC/UXO is weighed into decision making when selecting candidate sand sources for nourishment projects.

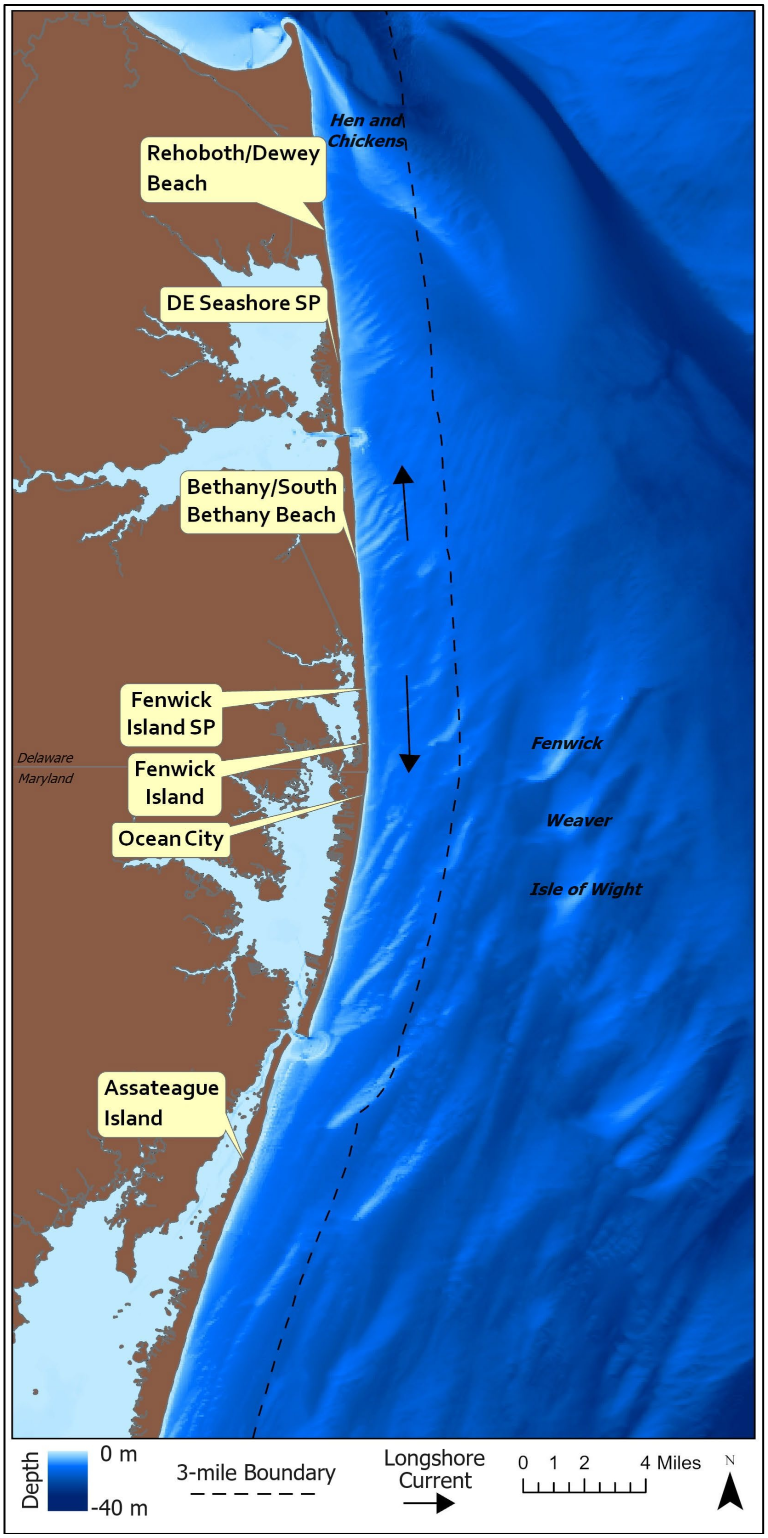

Figure 3-1. Overview of project study area with locations of current or potential beach nourishment sites. General longshore drift directions are indicated by black arrows, and the three-mile limit between state and federal waters is indicated by a dashed line. Major shoal structures of Hen and Chickens, Weaver, and Isle of Wight are also indicated.

3.2 Historical beach nourishment

The primary source of historical beach nourishment data used in this project was the American Shore and Beach Preservation Association's (ASBPA) National Beach Nourishment Database (Elko et al. 2021). This database is an excellent resource documenting beach nourishment projects around the United States that, in some cases, extends back as far as the early 20th century. Data entries are contributed by different entities in different states, often state environmental agencies. The DGS team downloaded all beach nourishment data for locations along the Atlantic coastlines of Delaware, Maryland, and the Delmarva Peninsula in Virginia.

Though it is an excellent data source, the ASBPA database does contain some data gaps. For example, borrow area information is lacking in many entries, especially older ones. In some entries planned sand volumes (i.e., those outlined in a dredging contract) were reported rather than the actual reported volumes dredged. Such discrepancies and data gaps needed to be filled to provide a more comprehensive picture of past beach nourishment activities and borrow area utilization. This was accomplished by reviewing project documents such as environmental impact statements and feasibility studies that were drafted close to the time that different nourishment projects were conducted. This review of secondary data sources helped improve our input data but required substantial effort, and we note that this should be factored into project planning for similar sand resource assessments in the future.

After preliminary review of the data, it was determined that many beach nourishments prior to the 1990s were sporadic, largely occurring in response to major storm surges that caused widespread erosion. Extensive dune construction and proactive nourishment activities first appeared in the 1990s. It was evident that small nourishments for small private beach communities represented a minor fraction of overall sand resource demand, as did nourishments using material from inland sand mines. For this reason, we focused our analysis on the four major beach nourishment areas within the study area: Ocean City, MD, Fenwick Island, DE, Bethany and South Bethany Beach, DE, and Rehoboth and Dewey Beach, DE. These four areas account for the overwhelming majority of offshore sand resource demand within the study area, and this demand has primarily developed in the last 30 years.

3.3 Sand needs forecasting

Studies of earth system model projections tend to indicate little change in the severity and frequency of tropical and extratropical cyclones in the coming century (Marsooli et al. 2019, Pringle et al. 2021). However, surge levels that were once uncommon (e.g., 100-year return intervals) are projected to greatly increase in frequency primarily as a result of sea level rise, with some estimates of historical 100-year flood return intervals shrinking to as little as 8 to 9-year return intervals (Marsooli et al. 2019). These increasingly common surges, generally below 1.8 m, can still cause substantial erosion to beaches. Our sand needs forecasts used 100-year storm surges as a trigger event for an emergency beach nourishment, as US Army Corps of Engineers (USACE) Atlantic coast protection plans conducted for coastal communities around 2000 often used this level of storm to estimate the necessary volumes and nourishment intervals along the coast of our study area.

3.3.1 Forecast scenarios

Given historic beach nourishment projects and climate projections in the region, the DGS team developed several scenarios to consider for future sand needs projections, named S1, S2, S3, and S4. Each scenario was "bootstrapped", or repeatedly simulated, over 1000 iterations to account for random variability in nourishment volumes and in timing of simulated storm surges that necessitate emergency beach nourishments. Final forecast predictions are reported as means, standard deviations, minima, and maxima of all 1000 iterations, allowing for a more comprehensive assessment of forecast uncertainty.

- The **S1** scenario is a simple projection of current sand usage from BUDM projects and nourishment programs in the four primary communities over the next century. It does not consider increasing sand needs due to increasingly frequent erosion events. The uncertainty from this scenario consists entirely of random variation in the volumes of sand used across nourishment projects for each site. This was simulated by randomly sampling within a normal distribution of nourishment volumes for each site, excluding small, localized nourishments and those that involved major dune reconstruction.

- The **S2** scenario is similar to the S1 scenario, but also includes a simulation of increasingly frequent 100-year storm surge events in the area, eventually reaching an 8.5-year return interval by 2100. The storm surges are incorporated into the sand needs forecasts by prompting an emergency nourishment event that may occur on years that are not part of the regular planned nourishment intervals from USACE assessments. For example, if Town X has a 4-year planned nourishment interval and a 100-year surge occurs 2 years after a planned nourishment, an emergency nourishment is triggered, the interval resets and the next nourishment will occur 4 years after the simulated 100-year storm surge.

- The **S3** scenario considers the same storm interval increases as S2, but with the addition of the Delaware Seashore SP beach and Fenwick Island SP beach as recipients of periodic nourishments. The reason for their inclusion is that these two state-managed lands abut Delaware Route 1, which is a major road with critical infrastructure importance. If this road was threatened by receding beaches it would almost certainly prompt protective measures, as Route 1 provides access to emergency services which would have to be rerouted all the way around Delaware's inland bays in the event of a road closure. Nourishment volumes for these areas were estimated based on the average volume of sand application per yard of beachfront reported for neighboring nourishment projects, with additional sand needed for initial dune or berm reconstruction. Note that the inclusion of these areas in S3 does not greatly affect sand needs forecasts for specific beaches, but rather the total cumulative volume of sand needed for the study region and the rate at which some sand sources might be depleted.

- The **S4** scenario uses the same approach as S3 but increases the rate of 100-year storm events to roughly once per year by 2100. This represents the worst-case climate predictions from Marsooli et al. (2019) for the Mid-Atlantic United States and would require both large volumes of sand and nearly constant nourishment projects by the end of the century.

Sand usage simulations were linked to whichever borrow area was most recently used for a given beach's nourishment project. When a simulation exhausted its assigned borrow area, the simulation would note that a new borrow area was needed. Each beach was assigned a "backup" borrow area based on proximity or past usage, which was then used in subsequent years in the simulation. If the backup borrow area was exhausted further along in the simulation, sand sources were assigned to a "deficit" category that indicates that a new, unknown source of sand would be needed. This allowed us to roughly estimate when certain borrow areas may be exhausted and when alternative sand sources would need to be considered.

3.3.2 Key forecast assumptions

All sand needs forecasts assumed that federal and state-managed sand sources could supply a maximum of 5% and 50% of their estimated volumes, respectively. The limit in federally-managed sources is based off of an environmental constraint limiting sand harvesting to 5% of total shoal volume in early agreements between BOEM and the state of Maryland. The limit in state-managed waters is based off a rough estimate of how much volume could feasibly be accessed by dredge operators. In discussions with Delaware sediment management experts this was agreed as a reasonable limit. However, it should be noted that many borrow areas in Delaware state waters have heterogeneous sand quality, and the actual feasible percentage sand volume yield from them is difficult to estimate. Similarly, the 5% limit in federal waters is not necessarily a permanent constraint; it may be increased or decreased as scientific understanding of the long-term environmental impacts of dredge activities improves. Additionally, potential issues like sand "armoring", where backwash from the screened dredge head creates a layer of gravel and stones that blankets the seafloor, may limit the amount of volume that can be extracted from a borrow area. Though significant armoring has not been observed in the study area during previous nourishments, it remains a concern for future resource planning.

Another key assumption is that borrow areas that have been used as sand sources will continue to deliver beach quality sand. This is particularly salient for Borrow Areas E and B in Delaware, which have only supplied sand for a few nourishment projects and have had issues with grain sizes and clay content in the past. Borrow Areas E and F also partially fall within a historic practice artillery range, and risks of frequent MEC/UXO encounters may limit the effective area where dredges may operate. If these borrow areas are deemed unsuitable in future dredging efforts, it will greatly reduce the theoretical availability of sand in Delaware state waters and necessitate an earlier shift to alternative sand sources.

Finally, we also assume that BUDM projects at the Ocean City and Indian River inlets will continue to provide adequate sand to meet the demands of the Assateague SP and North Indian River Inlet beaches, respectively. Given the frequency and small size of these projects, the forecasted volumes of sand needed are generally linear and much smaller than those of larger beach areas. Similarly, we assume that any historical sand source that has been deemed "Unusable", such as Little and Great Gull Bank, Hen and Chicken Shoals, and Maryland Borrow Areas 2, 3, and 9, will never be used as a source for future nourishments. It is possible that some of these sources may be revisited in the future, but we do not consider that to be an option in this analysis.

3.4 Assessing sand supply

Knowing that primary and backup sand sources for coastal communities in our study area will eventually run out, this project also aimed to identify potentially promising OCS areas that may be prioritized for investigations of sand resource potential and/or reserved from other OCS activities to avoid resource sterilization. This was accomplished by establishing statistical relationships between the composition of vibracore samples and their local bathymetric characteristics. These relationships were extrapolated to model a unitless index of sand resource potential. This process is summarized in Figure 3-2 and discussed in detail in this section.

3.4.1 Offshore core data

Offshore vibracore records are a key data source for assessing the sand resource potential of the seafloor. The DGS team reviewed a set of 527 vibracore descriptions that spanned from 1971 to 2017 in our internal databases. Core records had a higher density near the Delaware coast, but some records did extend far south and east into the study area.

First, core logs from within the study area were reviewed to assess the potential of each cored area as a sand resource. Cores were excluded from the set if they were less than 5 ft in length or had abundant void space in them. In some cases, cores corresponded to the same borehole, and in these cases, the lower core description was appended to the end of the upper core. Cores from outlet shoals were excluded, as these depositional environments were assumed to be different from the larger seafloor and are highly dynamic. Similarly, cores collected before the year 2001 were excluded, as seafloor features do shift over time. This restriction allowed us to only consider cores collected within roughly 10 years of the bathymetric data (~2009).

Core descriptions were broken down into their distinct segments. Each segment was graded based on its primary composition (e.g., sand, silt, clay, gravel, organics, or shell hash), described texture (e.g., very fine, coarse, medium), and secondary composition (e.g., silty, clayey, gravely). Primary compositions other than sand were deemed unacceptable and given a score of 0, while sands were given a score of 1. Sand textures were scored on a scale of 1 to 5. Core segments lacking a texture description were given a score of 1 as they generally corresponded to highly silty, clayey, or gravely sands. Intermediate scores were given to very fine, very coarse, and heterogeneous sands. A score of 5 was given to homogeneous fine, medium, and coarse sands, as these texture classes are believed to be representative of the native beach sands within the study region. Secondary compositions were scored on a scale of 1 to 5 based primarily on feedback from USACE personnel on the difficulties of working with different sediment mixtures. For example, core segments noted for abundant clay or compact sediments were scored a 1, as these can cause problems for dredges, while segments with some large gravel were given an intermediate score, as large gravel can be relatively easily screened during dredging. A secondary composition score of 5 was given to core segments with no secondary composition (i.e., pure sand), slight silt content, or slight small shell fragments. A quality measure was assigned to each core segment as:

$$Q = P * (T + S)$$

Where Q is the overall quality, P is the primary composition score, T is the sand texture score, and S is the secondary composition score.

These quality measures were multiplied by the respective length of their corresponding core segment. The sum of these weighted values was used as a composite score for sand resource quality. Maximum core length was limited to 10 feet because dredges generally are limited to several passes (each pass is usually 2-3 feet deep) for any given sand resource to limit pitting on the seafloor and the potential creation of dead zones. If any core segment had a score of 0 and a length greater than 0.5 feet, the remainder of the core was considered unacceptable. This cutoff was based on feedback from USACE personnel, who indicated that a dredge would likely move off of a sand source if sufficiently thick poor-quality sediments were encountered regardless of sand quality beneath this layer. Thus, each core score reflects a composite, unitless indicator of sand resource quality and quantity. The highest scores correspond to high quality, deep sand deposits. Intermediate scores correspond to low quality sands or thin high quality sand deposits. Low scores correspond to unusable or exceptionally thin sand deposits of minimal resource value. Reported core scores were normalized to a minimum of 0 and maximum of 1 to simplify ingestion into statistical models in subsequent analysis.

In addition to core descriptions, other data sources provided useful information for evaluating modeled potential offshore sand resource quality. Seismic survey lines provided a picture of the general structure of sand units on the seafloor. Seismic data were provided by multiple sources. Dredging Quality Management (DQM) data was investigated as an indicator of model output quality. DQM data provides GPS data of dredge movements and notes when the dredge pumps are actively running. Thus, areas with high dredge activity tend to indicate areas where suitable sand was found. By looking at DQM data submitted from dredging projects conducted after bathymetric data was collected, one can infer areas of high sand resource potential. These data were provided by BOEM via the USACE. A final source of model evaluation data were maps of sand resource units that were proven to provide quality sand in the past and offshore surficial geology maps for the state of Delaware. These data were accessed from the BOEM Data Center and the DGS, respectively.

3.4.2 Modeling sand resource quality scores

This study aimed to extrapolate information from the extensive dataset of offshore cores using statistical relationships between core characteristics (i.e., sediment composition and thickness of layers) and bathymetric features. The approach employed in this analysis is like approaches used in the field of digital soil mapping, which seek to extrapolate field observations of soil properties based on statistical relationships to ancillary spatial data, such as terrain morphological characteristics (McBratney et al. 2003). All bathymetric data and derivatives were sourced from a coastal topobathymetric digital elevation model compiled in the wake of Superstorm Sandy (OCM Partners 2015) which was primarily made up of a 1/3 arc-second coastal DEM collected in 2009 and centered offshore of Ocean City, MD (NOAA 2009). All data was resampled to 3 arc-second resolution (~90 m) and smoothed with a Gaussian filter to reduce bathymetric artifacts and inconsistencies between DEM tiles. Bathymetric derivatives that were considered as potential model predictors are presented in Table 3-1. The list includes a variety of derivatives that separate structures of the seafloor relative to surrounding areas and have been used in previous studies for modeling shoals, swales, reefs, and other common bathymetric features (Diesing et al. 2016; Koop et al. 2021; Pickens et al. 2021).

We used a random forests model to fit core scores of sediment quality to bathymetric derivatives. Random Forests is a classification and regression tree-based machine learning algorithm that utilizes a large set, or “forest”, of decision trees built on random subsets of the input data (Brieman 2001). The final prediction of a Random Forest represents the average prediction across all decision trees, making it resilient to overfitting from specific variable combinations. The random forests model was chosen for its ability to handle non-linear relationships between variables better than traditional linear regressions and its relative ease of implementation. Traditional multiple linear regression and more complex neural network models were also considered, but they were outperformed by random forests in early analyses. The model was developed using a 70%/30% training and testing set split of all input core data (n = 209). Pixel values of bathymetric derivatives were extracted to their corresponding cores. Variables were selected using an iterative, non-parametric variable selection process that identifies a small set of strong predictors while limiting variable redundancy. This process identified three powerful predictor variables (Table 3-1) of surface convexity calculated in a 25-pixel search radius, a multi-resolution bathymetric position index calculated over a 1 to 25-pixel radius, and surface ruggedness calculated over a 25-pixel radius. Bathymetric derivatives were generated in SAGA GIS (Conrad et al. 2015).

The 70% training dataset was then used to tune random forest model parameters of *mtry, ntree, minimum node size, maximum depth,* and *splitrule*. These model parameters dictate the degree of specificity and structure of the model. Tuning them is necessary to build a model specific enough to accurately predict sand resource quality in the input training dataset, yet general enough to provide reasonable predictions on external testing data. This was accomplished by creating a wide array of model parameter combinations and cycling through each combination using 5-fold cross validation. The combination of parameters that minimized model mean absolute error among cross validation folds was used for final model development. The final model was then used to make predictions on the 30% testing dataset, and these predictions were used for estimating final model prediction error and accuracy. Once trained, the model was extrapolated across the study area to produce a continuous map of predicted sediment quality at 90 m resolution. All statistical modeling was performed in R Statistical Software (R Core Team 2020) using the “ranger” package (Wright and Ziegler 2017).

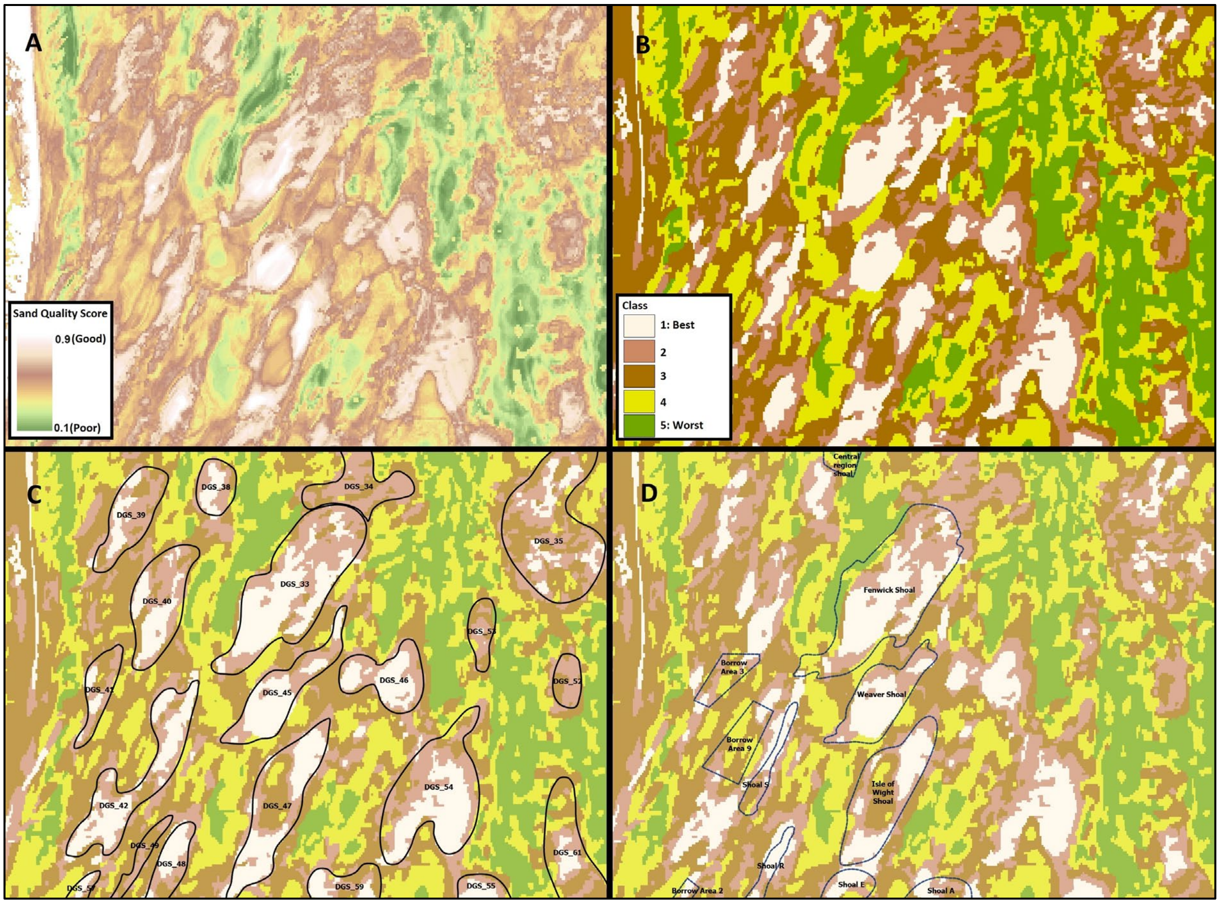

Figure 3-2. Example of the development of sand resource units from model outputs. The random forests model was used to generate a continuous predicted surface of sand resource quality scores (A), which was then subjected to an image segmentation algorithm to break the continuous surface into more easily interpretable clusters with similar features (B). These clusters were used to guide manual delineations of potential sand resource units (C), which were then compared to known shoals and borrow areas from previous investigations (D).

Table 3-1. Bathymetric derivatives considered in seafloor modeling efforts. Bolded variables indicate variables that were selected as model predictors by our variable selection process.

Variable Name	Variable Description
Depth	Depth from surface
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 3, 9, and **25-pixel** radii.
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 25-pixel radius. The advantage of this is that it can provide details on both coarse and fine topographic features.
Real Surface Area	The surface area of each pixel calculated based on its slope and curvature.
Slope	The maximum downhill angle of a pixel on the bathymetric surface.
Vector Ruggedness Measure	A measure of 3-dimensional terrain ruggedness evaluated in a 5 and **25-pixel** radius.

3.4.3 Delineation and categorization of sand resource units

After model extrapolation, an image segmentation with unsupervised classification algorithm was run on the model output to create localized clusters of modeled sand resource quality. This works by grouping pixels with similar features (in this case, modeled sand resource quality) into clusters dictated by input parameters. Input parameters, such as minimum cluster size, distance weighting, and number of classes, were tuned by trial-and-error until a satisfactory output was achieved. The goal of this tuning is to create discrete seafloor units of similar sand qualities that are easier to visualize. These clusters were then manually delineated into more cohesive and visually appealing sand resource units that could be stored as a set of polygon spatial features. Some of these delineated units aligned closely with previously identified shoals from the BOEM Data Center (Fig A-1; Table A-1), while others did not. Sand resource units that aligned with known shoals are noted in the attribute table of the associated Modeled_Sand_Resources shapefile. An example of this translation of model output to mapped sand units is presented in Figure 3-2. Note that even if a given area of the seafloor is not delineated as a sand resource unit, this does not necessarily mean that it is made up of unsuitable material. It simply means that the bathymetry-based model did not predict high quality sand resources in this area. Image segmentation and classification was performed in SAGA GIS (Conrad et al. 2015).

After manual delineation, sand resource units were compared to existing BOEM and DGS maps, core sample locations, and DQM data. These comparisons were used to categorize sand resource units as “Proven”, “Potential”, “Unverified Plus”, “Unverified”, or “Unusable” similar to the approach used in the USACE’s South Atlantic Division Sand Availability and Needs Determination (SAD SAND; USACE 2020). Table 3-2 provides a modified version of the SAD SAND report Table 3-3, indicating the categories and criteria used in that study and the present study.

Table 3-2. Summary of rules for assigned categories for sand resource units from the USACE South Atlantic Division sand needs assessment and this study.

Category	Confidence (%)	USACE SAD SAND Description	Present Study Description
Proven	90	Resource areas with beach-quality sand whose thickness and lateral extent have been fully determined through design-level geotechnical data and in most cases are permitted.	Sand units with abundant, high quality core data, DQM data indicating beach quality sand dredging has occurred onsite, AND/OR an area previously published with a BOEM categorization of “Proven”.
Potential	70	Resource areas with beach-quality sand whose existence has been verified through preliminary geotechnical and geophysical data (with vibracores approximately one mile apart). Thickness and/or lateral extent has been preliminarily determined.	Sand units that mostly to fully overlap an area previously published with a BOEM categorization of “Potential” AND high scores in model output with some corresponding core sample data indicating high sand quality.
Unverified Plus	5-30	Resource areas hypothesized to exist on the basis of geophysical evidence (seismic profiles, bathymetry, or side scan sonar) and at least one geotechnical core or surficial samples verifying beach-quality sand.	Sand units with high scores in model output AND containing at least one core sample indicating high quality sand. These units may partially overlap an area previously published with a BOEM categorization of “Potential”.
Unverified	0	Resource areas hypothesized to exist on the basis of indirect evidence for the presence of beach-quality sand.	Sand units with high scores in model output. These units may partially overlap an area previously published with a BOEM categorization of “Potential”.
Unusable	0	Unusable for one or more of the following reasons: 1. All beach-compatible material has been removed from the area prior to the SAND Study, 2. The sand source is inaccessible due to current conditions.3. Area was investigated and the presence of non-beach quality material throughout the area was verified.	Sand units that overlap an area previously published with a BOEM categorization of “Unusable”, or sand units with a mean depth over 30 meters.

3.4.4 Estimating sand resource unit volume

Traditionally, volumes of sand contained in a sand resource unit were estimated based on the thickness of sand measured from coring surveys and the geometry of the resource unit. However, this approach was not feasible in this project due to the large study area and limited core data far offshore. To overcome this limitation, we developed a GIS-based approach to estimate sand volume. Based on seismic data from the study region, it appeared that many sandy shoal units sit on top of dense, relatively flat sediment layers forming a "hump" of sand. Our approach extracted local depth data from the low-lying seafloor along the perimeter of each sand resource unit. Depth values were filtered to remove particularly deep or shallow areas to avoid over- or underestimating the sand resource unit volume. Filtered depth values were Kriged (a common form of spatial interpolation) to simulate the base seafloor underlying the raised shoal features. This layer was then subtracted from the bathymetric data for each shoal to create a prism of sediment volume. This method was evaluated using known shoals with volumes estimated based on core data (Cleaves et al. 2000). It should be noted that this approach only considers this sandy material that sits above the surrounding seafloor, and it may underestimate sand volume in shoals that sit atop additional deeper layers of sand. We emphasize that sand resource volumes estimated in this way are rough estimates, and geological surveys are necessary for confirming the composition and structure of any potential sand resource unit.

4 Results and Discussion

4.1 Sand needs for each nourishment area

Table 4-1 reports estimated sand volumes used by each nourishment area within the study area between 1991 and 2021. Tables 4-2 and 4-3 report the average, minimum, and maximum years when primary and backup sand sources may be exhausted for different nourishment areas in each bootstrapped forecast. In the following sections we will discuss the results of the sand needs forecasts for each nourishment area individually and provide overall estimates of total sand needs for the entire study region. Tables 4-4 to 4-7 provide estimates of cumulative sand needs by 2100 for each area under each forecasting scenario. Aggregated across the four major beach nourishment areas (i.e., Ocean City, Fenwick Island, Bethany/South Bethany Beach, Rehoboth/Dewey Beach), we estimate that from 1991 to 2021 roughly 33.1 million cy of sand was dredged and distributed. A large portion of this 33.1 million cy is made up of material that was used in major dune/berm reconstruction projects in the early 2000s, with smaller volume periodic nourishments intended to absorb major storm surges without significantly eroding these constructed dunes. Bootstrapped forecasting simulations estimated that these sites will require between (minimum – maximum estimates) 40.9 - 53.0, 41.4 - 62.4, 44.2 - 72.2, and 77.5 - 139.4 million cy of sand under parameters of S1, S2, S3, and S4, respectively. However, if additional large-scale dune/berm reconstructions are necessary in the future, these numbers may increase.

Table 4-1. Estimated sand volumes used for each beach nourishment area from 1991 to 2021. Volumes are expressed in millions of cubic yards (cy).

Area	Volume Used 1991-2021 (million cy)
Ocean City	13.9
Fenwick Island	2.3
Bethany/S. Bethany	9.5
Rehoboth/Dewey	7.4
Delaware Seashore SP	0
Fenwick Island SP	0
Ocean City Inlet	2.7
Indian River Inlet	3.1

Table 4-2. Average forecasted year (and minimum and maximum) across bootstrap iterations when <u>backup</u> sand sources will be needed to meet demand under each forecast scenario. Source abbreviations and descriptions are included in Table 3-8.

Area	Primary Source	S1	S2	S3	S4
Ocean City*	BOEM_WV	2025 (‘25-‘25)	2025 (‘25-‘25)	2025 (‘24-‘25)	2025 (‘24-‘25)
Fenwick Island	DE_F	2091 (’84-’96)	2088 (’78-’96)	2085 (’73-’96)	2069 (’58-’81)
Bethany/S. Bethany	DE_E	2067 (’63-’72)	2066 (’58-’72)	2063 (’53-’69)	2057 (’47-’66)
Rehoboth/Dewey	DE_BN	2059 (’48-’75)	2058 (’45-’72)	2055 (’40-’72)	2051 (’40-’66)
DE Seashore SP	DE_BN	-	-	2055 (’40-’72)	2051 (’40-’66)
Fenwick Island SP	DE_E	-	-	2063 (’53-’69)	2057 (’47-’66)

*Ocean City currently receives sand from Weaver Shoal in federal waters. The volume already dredged from this sand source is close to the 5% limit placed on sand resources in federal waters in this region.

Table 4-3. Average forecasted year (and minimum and maximum) across bootstrap iterations when unknown sand sources will be needed to meet demand under each forecast scenario. Source abbreviations and descriptions are included in Table 3-8.

Area	Backup Source	S1	S2	S3	S4
Ocean City	BOEM_IW	2054 (‘49-‘61)	2054 (’44-’61)	2053 (’43-’61)	2048 (’37-’57)
Fenwick Island	BOEM_FI	-	-	-	-
Bethany/S. Bethany	DE_F	2091 (’84-’96)	2088 (’78-’96)	2085 (’73-’96)	2069 (’58-’81)
Rehoboth/Dewey	DE_F	2091 (’84-’96)	2088 (’78-’96)	2085 (’73-’96)	2069 (’58-’81)
DE Seashore SP	DE_G	-	-	-	-
Fenwick Island SP	DE_G	-	-	-	-

Table 4-4. Cumulative sums of forecasted sand needs for each nourishment area under scenario S1 from 2021 to 2100. Values represent the mean, standard deviation, minimum, and maximum estimates from 1000 forecast simulation bootstrap iterations. All numeric units are millions of cubic yards.

Area	Mean Total	SD Total	Minimum Total	Maximum Total
Ocean City	18.8	0.7	16.7	21.0
Fenwick Island	6.4	0.3	5.5	7.2
Bethany/S. Bethany	12.5	0.2	11.7	13.3
Rehoboth/Dewey	9.3	0.7	7.0	11.5
Delaware Seashore SP	-	-	-	-
Fenwick Island SP	-	-	-	-
Ocean City Inlet	4.9	0.2	4.1	5.8
Indian River Inlet	7.7	0.1	7.2	8.2

Table 4-5. Cumulative sums of forecasted sand needs for each nourishment area under scenario S2 from 2021 to 2100. Values represent the mean, standard deviation, minimum, and maximum estimates from 1000 forecast simulation bootstrap iterations. All numeric units are millions of cubic yards.

Area	Mean Total	SD Total	Minimum Total	Maximum Total
Ocean City	20.8	1.3	17.1	25.4
Fenwick Island	6.8	0.4	5.7	8.5
Bethany/S. Bethany	13.2	0.6	11.8	15.0
Rehoboth/Dewey	9.9	0.8	6.9	13.5
Delaware Seashore SP	-	-	-	-
Fenwick Island SP	-	-	-	-
Ocean City Inlet	4.9	0.2	4.1	5.8
Indian River Inlet	7.7	0.1	7.2	8.2

Table 4-6. Cumulative sums of forecasted sand needs for each nourishment area under scenario S3 from 2021 to 2100. Values represent the mean, standard deviation, minimum, and maximum estimates from 1000 forecast simulation bootstrap iterations. All numeric units are millions of cubic yards.

Area	Mean Total	SD Total	Minimum Total	Maximum Total
Ocean City	20.9	1.3	16.9	25.2
Fenwick Island	6.8	0.5	5.6	8.6
Bethany/S. Bethany	13.2	0.5	11.8	15.4
Rehoboth/Dewey	9.9	0.8	7.3	12.8
Delaware Seashore SP	3.7	1.2	1.7	6.5
Fenwick Island SP	2.1	0.7	0.9	3.7
Ocean City Inlet	4.9	0.2	4.1	5.8
Indian River Inlet	7.7	0.1	7.2	8.2

Table 4-7. Cumulative sums of forecasted sand needs for each nourishment area under scenario S4 from 2021 to 2100. Values represent the mean, standard deviation, minimum, and maximum estimates from 1000 forecast simulation bootstrap iterations. All numeric units are millions of cubic yards.

Area	Mean Total	SD Total	Minimum Total	Maximum Total
Ocean City	43.5	3.0	33.9	53.3
Fenwick Island	14.2	1.1	10.1	18.5
Bethany/S. Bethany	22.5	1.3	18.8	26.6
Rehoboth/Dewey	16.9	1.4	12.1	21.8
Delaware Seashore SP	7.1	2.7	1.7	12.3
Fenwick Island SP	4.0	1.5	0.9	6.9
Ocean City Inlet	4.9	0.2	4.1	5.8
Indian River Inlet	7.7	0.1	7.2	8.2

4.1.1 Sand needs: Ocean City, Maryland

Ocean City has the largest forecasted sand needs of all areas considered in this study and is the largest stretch of beach receiving nourishments in our study area. As with the other beaches, forecasts of sand needs under all scenarios generally track the USACE baseline estimate until around 2050, when S2, S3, and especially S4 begin to diverge upward (Fig 4-1). The bootstrapped forecasting simulations estimated that Ocean City will require (mean ± 1 S.D.) 18.8 ± 0.7, 20.8 ± 1.3, 20.9 ± 1.3, and 43.5 ± 3.0 million cy of sand by 2100 for S1, S2, S3, and S4 scenarios, respectively. These volumes are forecasted needs beyond the estimated 13.9 million cy dredged between 1991 and 2021 (Table 4-1).

Ocean City's current sand source, Weaver Shoal, is expected to reach the 5% dredging limit by 2025, which will prompt a shift to its backup sand source, Isle of Wight Shoal. If the 5% federal dredging limit is maintained throughout the next century, our forecasts estimate that an additional sand source will be needed around 2054 (S1) or 2048 (S4; Table 4-3). The deficit of additional sand needed by Ocean City in excess of current or backup borrow area supply is forecasted to reach 10.6 ± 0.8, 12.5 ± 1.4, 12.6 ± 1.3, and 35.2 ± 3.0 million cy for S1, S2, S3, and S4, respectively. However, Ocean City has a larger number of potential sand sources in nearby federal waters relative to the other major beaches in the study area. Notably, Shoal A (Table 4-8) was noted as a possible sand source for Ocean City in a 2008 feasibility study, but it was not chosen due to its distance from the placement site. The key limitation for identifying additional long-term sand sources for the Ocean City is competing uses of these offshore areas and limited geologic data to confirm sand resource quality in many of these shoals.

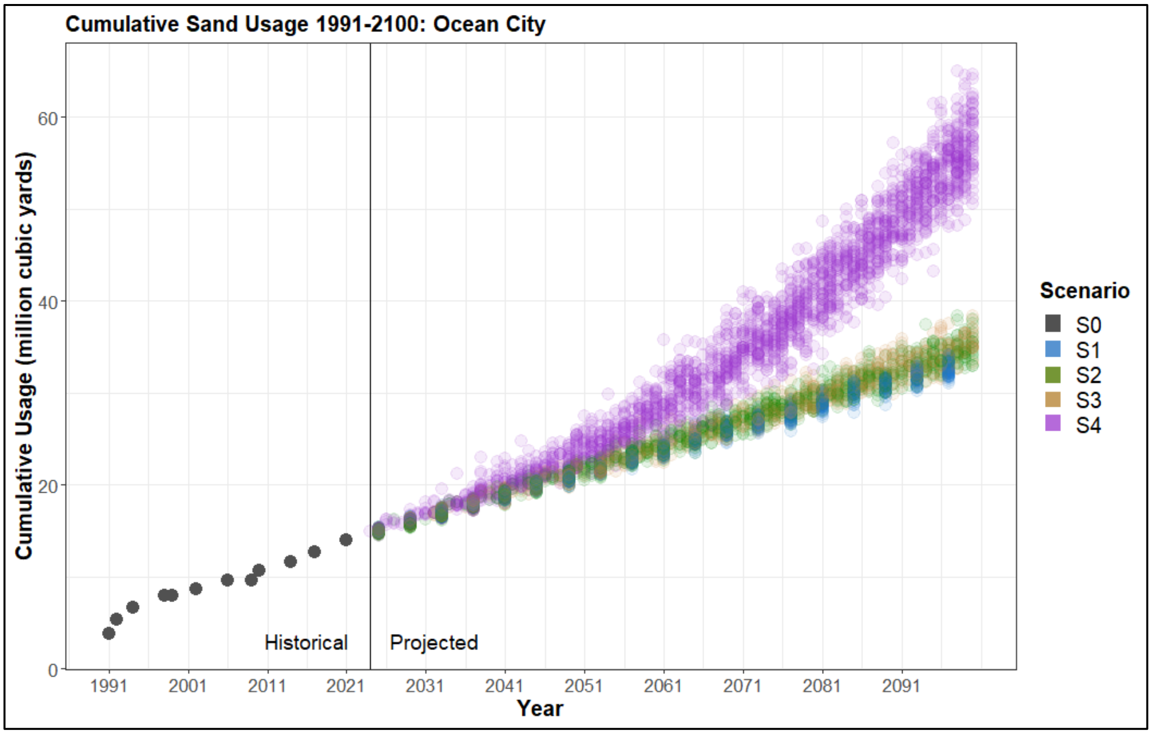

Figure 4-1. Forecasted cumulative usage needs for Ocean City, MD. The spread of points indicates the random variation across 1000 bootstrapped forecast simulations. Grey points correspond to "S0", or known nourishments prior to 2021, while blue, green, yellow, and magenta points correspond to forecasts from S1, S2, S3, and S4 scenarios.

4.1.2 Sand needs: Fenwick Island, Delaware

Fenwick Island forecasts of sand needs under all scenarios also generally track the USACE baseline estimate until around 2050, when S2, S3, and especially S4 begin to diverge upward (Fig 4-2). The bootstrapped forecasting simulations estimated that Fenwick Island will require (mean ± 1 S.D.) 6.4 ± 0.3, 6.8 ± 0.4, 6.9 ± 0.5, and 14.2 ± 1.1 million cy of sand by 2100 for S1, S2, S3, and S4 scenarios, respectively. These volumes are forecasted needs beyond the estimated 2.3 million cy dredged between 1991 and 2021.

Fenwick Island's current sand source, Borrow Area F, is forecasted to meet the nourishment needs of the beach until late in the 21st century for S1 through S3, but as early as 2069 for S4 as it serves as a backup source for other nourishment areas. Borrow Area F is suspected to contain a large amount of high-quality sand, with an estimated volume of 40 million cy. However, this borrow area has been heavily utilized by Delaware beaches in recent years. If current sand sources for other Delaware beaches prove to be too low quality or have other issues, it is possible that Borrow Area F will be used for their projects as well. Such a change would significantly reduce the effective lifetime of this sand resource. Additionally, Borrow Area F is known to intersect an area of potential MEC/UXO contamination. Although there have not been any major problems due to this, it is an ongoing concern that may also limit the effective lifetime of this sand source. Fenwick Island is relatively close to the federally-managed Fenwick Shoal, which may serve as an alternative sand source if needed in the future. We did not forecast a deficit beyond primary and backup sand sources for Fenwick Island in any scenario, under the assumption that the federally-managed Fenwick Shoal could be used as a backup source after the exhaustion of Borrow Area F.

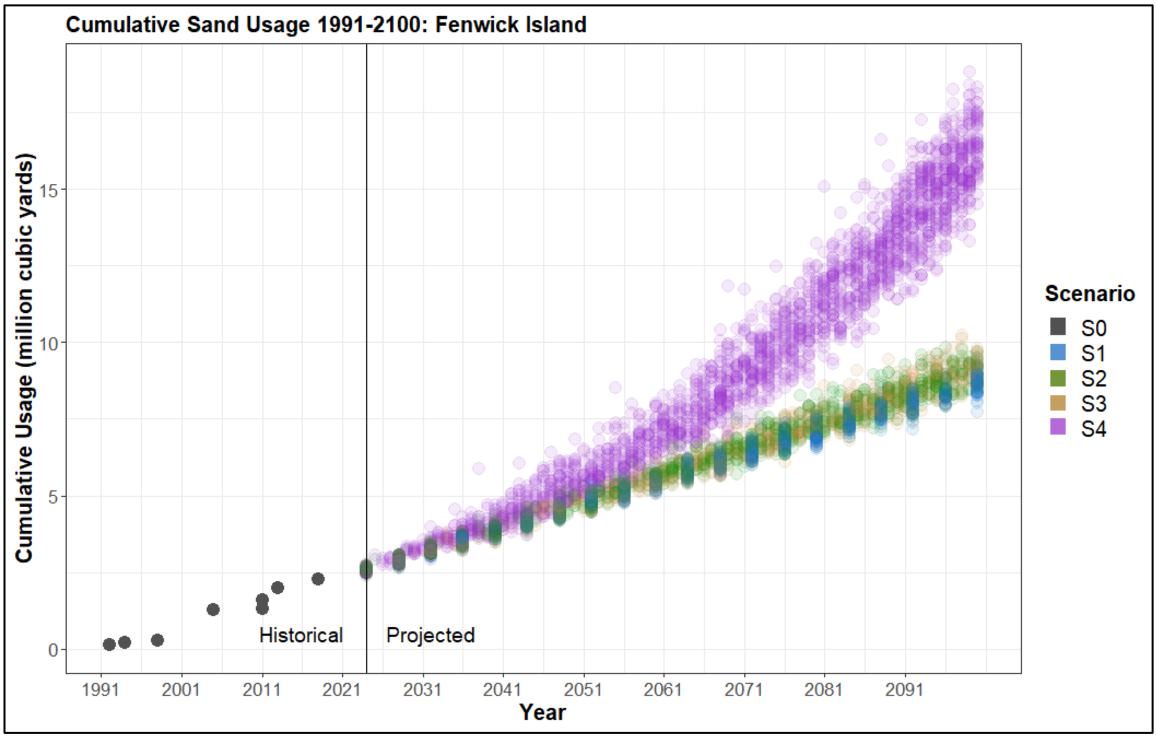

Figure 4-2. Forecasted cumulative usage needs for Fenwick Island, DE. The spread of points indicates the random variation across 1000 bootstrapped forecast simulations. Grey points correspond to "S0", or known nourishments prior to 2021, while blue, green, yellow, and magenta points correspond to forecasts from S1, S2, S3, and S4 scenarios.

4.1.3 Sand needs: Bethany and South Bethany, Delaware

Bethany and South Bethany Beach forecasts of sand needs under all scenarios also generally track the USACE baseline estimate until around 2050, when S2, S3, and especially S4 begin to diverge upward (Fig 4-3). The bootstrapped forecasting simulations estimated that the Bethany and South Bethany shoreline will require (mean ± 1 S.D.) 12.5 ± 0.2, 13.2 ± 0.6, 13.2 ± 0.5, and 22.5 ± 1.3 million cy of sand by 2100 for S1, S2, S3, and S4 scenarios, respectively. These volumes are forecasted needs beyond the estimated 9.5 million cy dredged between 1991 and 2021.

The current sand source for Bethany and South Bethany Beach is Borrow Area E (Table 4-8). This borrow area has an estimated volume of 25 million cy, but it occupies an area of heterogeneous seafloor sediment and has had inconsistent results as a sand source in the past. Under our forecast scenarios (and assumptions), we predict that Borrow Area E may continue to meet Bethany and South Bethany Beach's sand demands until 2067 (S1) or 2057 (S4; Table 4-2). Like Borrow Area F, Borrow Area E falls within an area of potential MEC/UXO. Screening protocols are in place for dredge operations to avoid taking potential hazards into the dredge pumps, but if substantial issues arise with MEC/UXO contamination or screening practices cause armoring of the seafloor, it may limit the effective lifetime of the sand source. The heterogeneity of sand quality within this borrow area may also limit its effective lifetime (See Section 4.3). If dredge operators must spend a long time searching for quality sand deposits, costs may increase, making Borrow Area E a less attractive option as a sand source. Bethany Beach has used Borrow Area F as a sand source in the past and may do so again in the future if needed. As the largest beach nourishment area in Delaware, such a shift would likely shorten the effective lifetime of Borrow Area F substantially. All scenarios forecast a deficit beyond current or backup borrow area supply for Bethany and South Bethany Beach of roughly 1.3, 2.1, 2.5, and 12.0 million cy for S1, S2, S3, and S4, respectively (Table 4-8).

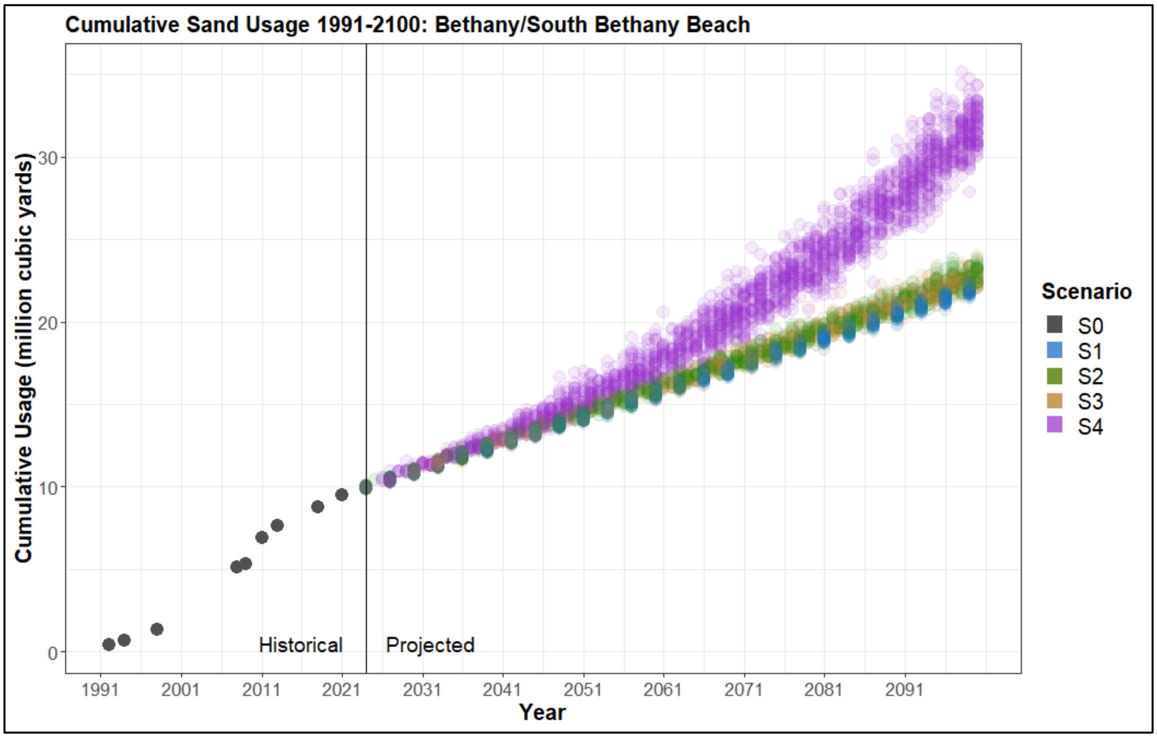

Figure 4-3. Forecasted cumulative usage needs for Bethany and South Bethany Beach, DE. The spread of points indicates the random variation across 1000 bootstrapped forecast simulations. Grey points correspond to "S0", or known nourishments prior to 2021, while blue, green, yellow, and magenta points correspond to forecasts from S1, S2, S3, and S4 scenarios.

4.1.4 Sand needs: Rehoboth and Dewey Beach, Delaware

Rehoboth and Dewey Beach forecasts of sand needs under all scenarios also generally track the USACE baseline estimate until around 2050, when S2, S3, and especially S4 begin to diverge upward (Fig 4-4). The bootstrapped forecasting simulations estimated that the Rehoboth and Dewey shoreline will require (mean ± 1 S.D.) 9.3 ± 0.7, 9.9 ± 0.8, 9.9 ± 0.8, and 16.9 ± 1.4 million cy of sand by 2100 for S1, S2, S3, and S4 scenarios, respectively. These volumes are forecasted needs beyond the estimated 7.4 million cy dredged between 1991 and 2021.

The current sand source for Rehoboth and Dewey Beach is Borrow Area B (north) in Delaware waters. This borrow area has shifted over time; it was originally removed from consideration due to the presence of hard bottom habitats (e.g., relic corals, mussel beds) but later redrawn after an alternative source, Borrow Area G, yielded unacceptably coarse beach fill material. Like Borrow Area E, this borrow area sits in the heterogeneous seafloor environment found landward of Hen and Chickens shoal, containing only minor finger shoals compared to the larger shoal structures to the south (See Section 4.3). Borrow Area B is relatively small (estimated 11 million cy), and it remains to be seen how much of its volume may feasibly be extracted before logistical or sand quality challenges make it unusable. Under our forecast scenarios (and assumptions), we predict that Borrow Area B may continue to meet the area's sand demands until 2059 (S1) or 2051 (S4; Table 4-2). All scenarios forecast a deficit beyond current or backup borrow area supply for Rehoboth and Dewey Beach of roughly 1.0, 1.5, 1.9, and 9.0 million cy for S1, S2, S3, and S4, respectively (Table 4-8).

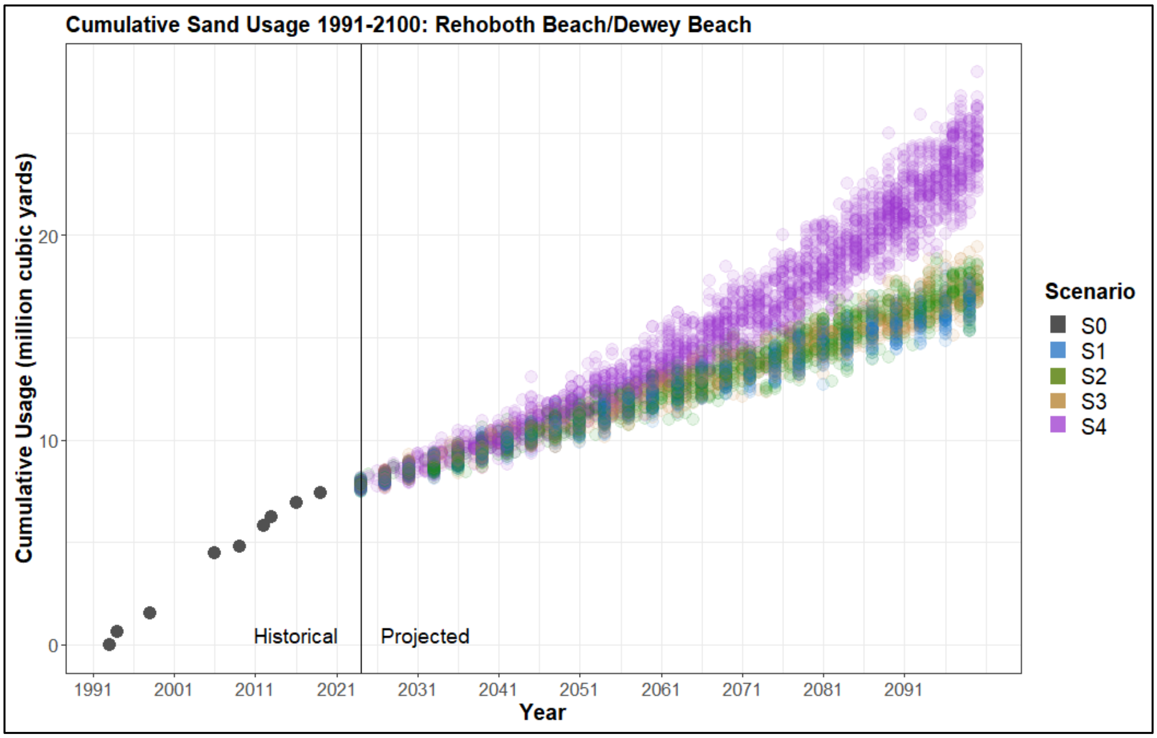

Figure 4-4. Forecasted cumulative usage needs for Rehoboth and Dewey Beach, DE. The spread of points indicates the random variation across 1000 bootstrapped forecast simulations. Grey points correspond to "S0", or known nourishments prior to 2021, while blue, green, yellow, and magenta points correspond to forecasts from S1, S2, S3, and S4 scenarios.

4.1.5 Sand needs: Fenwick Island and Delaware Seashore State Parks, Delaware

Beach nourishment of the two state parks along Route 1 in Delaware was only incorporated into S3 and S4, as these two areas do not currently receive beach nourishment. Primary borrow areas for each site were assigned based on proximity, with Delaware Borrow Area G as a backup source. Borrow Area G was discontinued after it was used for dune construction and as a nourishment source for Rehoboth and Dewey Beach in the early 2000s and found to yield overly coarse material. However, it is close to both state parks and may be considered as an emergency source in the distant future.

Under S3 parameters, we estimated that by 2100 Fenwick Island and Delaware Seashore State Parks would require roughly (mean ± 1 S.D.) 2.1 ± 0.7 and 3.7 ± 1.2 million cy of sand or beach fill material, respectively. Under S4 parameters, the estimated sand needs of Fenwick Island and Delaware Seashore State Parks increase to roughly 4.0 ± 1.5 and 7.1 ± 2.7 million cy, respectively (Table 4-6, 4-7).

4.1.6 Sand needs: Ocean City Inlet and Indian River Inlet

This study operated under the assumption that current sand bypass, inlet, harbor, and ebb shoal dredging will continue to provide adequate volumes of sand for beaches near Ocean City Inlet and Indian River Inlet over the forecasted period. The Ocean City Inlet projects deposit sand on the south end of the inlet at Assateague State Park, and the Indian River Inlet bypass project deposits sand north of the inlet on Coin Beach in Delaware Seashore State Park. These projects employ frequent, small amounts of sand to mitigate uneven erosion of the beaches caused by the jetties that stabilize the inlets. Sand is sourced from inlet ebb shoals, inlet/harbor dredging, and depositional areas immediately adjacent to the jetties. These are dynamic depositional environments, so it is difficult to estimate the long-term sand volumes that they may supply. Due to the high frequency of nourishments for these projects (sometimes twice per year), there was very little variability in forecasted sand needs among the different forecast scenarios. We estimate that the Ocean City and Indian River inlet projects will cumulatively require roughly 3.1 and 7.5 million cy of sand by 2100 in addition to the estimated 2.7 and 3.1 million cy already dredged, respectively. As mentioned previously, our forecasts operate under the assumption that these localized sand sources will continue to supply the necessary volumes of sand to sustain these nourishment activities into the future.

4.2 Sand supply from past and present sources

Table 4-8 reports the lifetime sand demand for sand sources within the study area through 2100, as well as forecasted sand deficits for different nourishment areas under each forecast scenario. This information provides both an estimate of sand needs and highlights which sand resources are most heavily relied upon, and therefore most sorely missed if issues arise, in our forecasts over the coming decades. Notably, our forecasts rely on Delaware's Borrow Area F supplying roughly 20.4 to 20.6 million cy of sand by 2100 and Delaware's Borrow Areas E and B supplying 12.7 and 5.8 million cy, respectively. Borrow Area F has already been used for several nourishments and serves as a primary sand source for Fenwick Island and backup source for Rehoboth/Dewey and Bethany/South Bethany beaches. While Borrow Area F has been relatively reliable as a sand source, areas E and B have had issues in the past. If one of one or both borrow areas prove to be logistically infeasible as sand sources in the future, it will place additional strain on Borrow Area F and necessitate an earlier shift to alternative OCS sand sources than originally forecasted. As we will discuss in the upcoming section, Delaware's borrow areas sit on heterogeneous sand deposits of rippling sheet sands that overlap with muddy paleo-channel deposits in some places (Mattheus et al. 2020), while larger consolidated shoal structures are more common to the south.

Table 4-8. Cumulative sand volumes required from different borrow areas under different forecasting scenarios by 2100. Values represent the average (standard deviation) of sand demand across bootstrapping iterations in units of millions of cubic yards. Borrow areas that are exhausted in the simulation are noted, as are borrow areas that were deemed unusable at the beginning of this study. The "Deficit" group refers to the total cumulative volume of sand needs not accounted for by primary or backup sand sources for a given nourishment area. Estimated initial volumes based on core data are also provided in units of million cy.

Source Group	Source Name	Source ID	S1	S2	S3	S4	Initial Volume
BOEM	Fenwick Island Shoal	BOEM_FI	0.8 (0.2)	1.1 (0.4)	1.4 (0.5)	7.9 (1.0)	211
BOEM	Great Gull Bank	BOEM_GG	2.0 (0)^	2.0 (0)^	2.0 (0)^	2.0 (0)^	63
BOEM	Isle of Wight Shoal	BOEM_IW	7.0 (0.3)*	7.0 (0.3)*	7.0 (0.3)*	7.0 (0.3)*	136
BOEM	Weaver Shoal	BOEM_WV	5.3 (0.2)*	5.3 (0.2)*	5.3 (0.2)*	5.3 (0.2)*	93
Delaware	Borrow Area B (North)	DE_BN	5.7 (0.1)+	5.7 (0.1)+	5.9 (0.4)+	5.8 (0.4)+	11
Delaware	Borrow Area E	DE_E	12.7 (0.1)+	12.7 (0.1)+	12.8 (0.2)+	12.8 (0.2)+	25
Delaware	Borrow Area F	DE_F	20.4 (0.3)+	20.4 (0.3)+	20.5 (0.3)+	20.6 (0.4)+	40
Delaware	Borrow Area G	DE_G	2.9 (0)^	2.9 (0)^	7.7 (1.0)	13.4 (3.6)	90
Delaware	Borrow Area A	DE_A	1.5 (0)^	1.5 (0)^	1.5 (0)^	1.5 (0)^	10
Maryland	Borrow Area 2	MD_B2	3.8 (0)^	3.8 (0)^	3.8 (0)^	3.8 (0)^	-
Maryland	Borrow Area 3	MD_B3	2.5 (0)^	2.5 (0)^	2.5 (0)^	2.5 (0)^	-
Maryland	Borrow Area 9	MD_B9	4.2 (0)^	4.2 (0)^	4.2 (0)^	4.2 (0)^	-
Maryland	Ocean City Inlet (MD)	MD_OC	5.8 (0.2)	5.8 (0.2)	5.8 (0.2)	5.8 (0.2)	-
Delaware	Indian River Inlet (DE)	DE_IR	10.7 (0.1)	10.7 (0.1)	10.7 (0.1)	10.7 (0.1)	-
Deficit	Ocean City	oc_def	10.6 (0.8)	12.5 (1.4)	12.6 (1.3)	35.2 (3.0)	-
Deficit	Rehoboth/Dewey	rd_def	1.0 (0.4)	1.5 (0.5)	1.9 (0.7)	9.0 (1.2)	-
Deficit	Bethany/South Bethany	bb_def	1.3 (0.4)	2.1 (0.6)	2.5 (0.8)	12.0 (1.4)	-

^Deemed unusable due to ecological concerns, poor material quality, or previous resource exhaustion
*Exhausted by 2100 at 5% limit for dredging of total shoal volume based on federal regulations
+Exhausted by 2100 at 50% limit for dredging of total shoal volume based on theoretical efficiency limits

4.3 Modeled sand resource units

4.3.1 Model performance and post processing

The random forests model achieved a testing set mean absolute error and R-squared of 0.22 and 0.28, respectively, and a training set mean absolute error and R-squared of 0.21 and 0.49, respectively. These R-squared values are typical in the field of digital soil mapping when seeking relationships between terrain morphology and soil properties, as there are many environmental factors that affect spatial distributions of sediments and soils that the model cannot account for. The goal of this modeling, and of digital soil mapping in general, is to identify regions where we would be more likely to encounter high quality sand, which can aid in designing targeted field sampling campaigns and building offshore management strategies.

We used segmentation and classification of the model predictions across the study area to create discrete sand units that may be investigated as sand resources in the future. The segmented model output may also be helpful for planning dredge operations and borrow area expansions in areas that contain a heterogeneous mix of seafloor features and sediments. For example, our model predictions suggest that proposed expansions of Borrow Areas E and F are particularly promising directly north and south of Borrow Area E and east and northeast of Borrow Area F (Fig 4-5). This output is shared as supplemental data to this report.

In total, we identified 158 potential sand resource units (Fig A-2) and assigned identifiers as DGS_1 through DGS_158. Some modeled sand resource units corresponded to known sand resources (e.g., DGS_33 and Fenwick Shoal or DGS_45 and Weaver Shoal; Fig 3-2), while others often intersected shoals modeled by Pickens et al. (2021). Both Known and Modeled sand resource polygons are included in the accompanying geodatabase deliverable, and we note known shoals that intersected our modeled sand units in the "Known Overlap" column of the accompanying Modeled Sand Resource Units feature layer. We also note potential conflicts from MEC/UXO, wind energy lease boundaries, marine sand lease areas, nearby reef habitats, and intersections with suspected paleochannel deposits, which tend to underly surficial sand with dense, muddy material unsuitable for beach nourishment. We do not note potential habitat or cultural resource concerns beyond this, and we emphasize the importance of comprehensive site surveys to quantify potential impacts of dredge activities over any sand resource unit being considered as a sand source.

Many of the sand resource units delineated from our model output are quite distant (15+ miles) from beach nourishment sites. These areas are not discussed in detail in this report for several reasons, but they are included in the accompanying shapefile. Primarily, distant areas are likely impractical as sand sources due to the high expenses of deep water dredging and long-distance sand pumping with current technology, and they often conflict with offshore wind energy lease areas, which may prevent them from serving as sand sources in the future. Additionally, core data becomes increasingly sparse as distance from shore increases. This means that there was less representation of distant cores in our model training datasets. Sediment texture may become finer with increasing distance from shore due to sediment transport dynamics, but our model cannot account for this due to limited training data. It is possible that our model may overestimate sand resource quality in these distant areas.

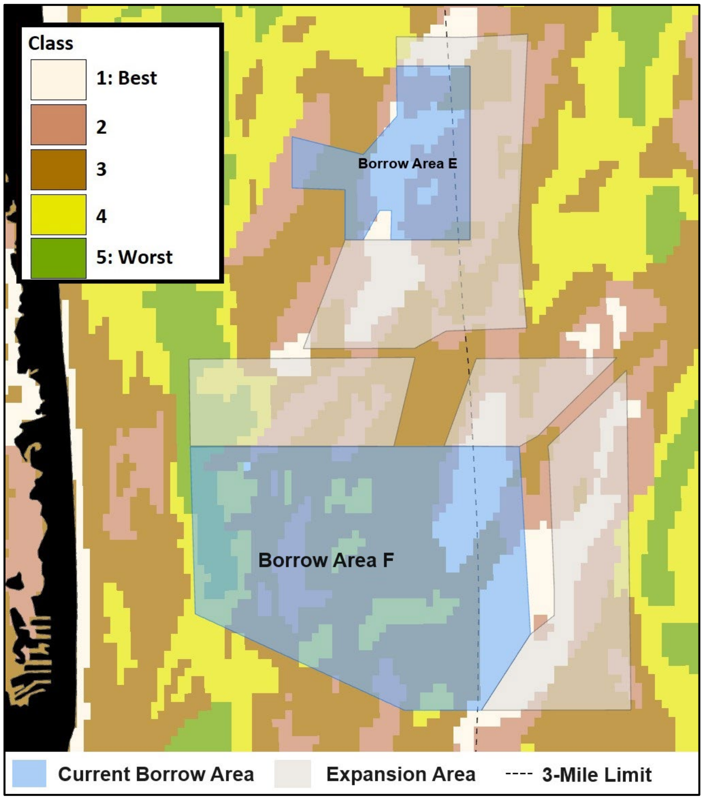

Figure 4-5. Potential expansions of Delaware Borrow Areas E and F. Model predictions (class 1-5) suggest high quality (white and light tan) material to the north and south of Borrow Area E and to the east and northeast of F. This serves as an example of how bathymetric modeling may help guide sand resource planning for both state and federal waters.

4.3.2 Sand resource unit volume estimates

Sand resource unit volumes estimated based on the interpolated shoal perimeter bathymetry showed agreement with the traditional approach (Fig 4-6). This approach only captures the volume of a sand resource unit that sits above an interpolated surface of low-lying areas along its perimeter and thus does not include deeper sands or sand beds lying beneath raised seafloor sand features. This may explain why estimates for our interpolation approach were generally lower than those made using core data for estimating sand thickness and shoal volume (Fig 4-6). However, we believe that systematic underestimation of sand volumes is preferable to overestimation as it allows us to be more conservative in assessments of potential sand resource supply. Additionally, it should not be assumed that one hundred percent of a sand resource unit's estimated volume is beach quality sand, as it captures all raised features above the surrounding seafloor.

Across entire the study area, all DGS-delineated sand resource units totaled 5.8 billion cy. 790, 600, 610, and 350 million cy fell within roughly 10 miles of Ocean City, Fenwick Island, Bethany/South Bethany Beach, and Rehoboth/Dewey Beach, respectively. However, these sums do not reflect sand resources that are off limits due to competing interests or other limitations, and individual volume predictions likely have a substantial margin of error. In the next section we will discuss potential additional sand resource units for each major beach nourishment area in the study area, as well as the concerns and potential limitations of these sand resource units.

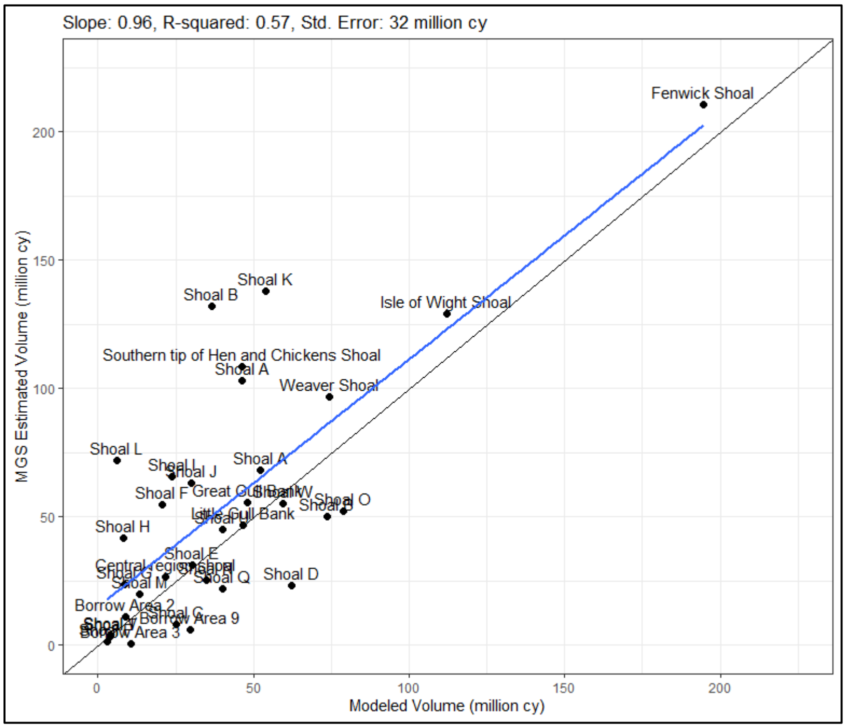

Figure 4-6. Comparison of estimated sand resource volumes as estimated by BOEMs sand resources and through a bathymetric perimeter interpolation approach (Modeled Volume) developed in this work. The blue line represents the linear fit between predictions, while the black line is the 1:1 line. The slight elevation of the blue line over the black line indicates a tendency of the modeled volume to underestimate volumes estimated based on core characteristics.

4.3.3 Potential future sand resources for each nourishment area

4.3.3.1 Future sand resources: Ocean City, Maryland

Beyond the current and backup borrow areas in Weaver and Isle of Wight Shoals (DGS_45 and DGS_47), several other federally-managed shoals have been considered as Ocean City sand sources in the past. Relative to the beach nourishment sites in Delaware, OCS sand resources off Ocean City tend to be well-defined, large shoal structures. Previous feasibility studies have excluded Fenwick Shoal (DGS_33) due to concerns of MEC/UXO and its possible use as a sand resource for Delaware beach nourishments in the future. Other candidate sand sources in previous feasibility studies included Shoals A and B (DGS_58, DGS_59, and DGS_60), however these are slightly further from Ocean City than other sources and abut large artificial reefs that serve as important habitat and recreational fishing areas (Fig 4-7). Our model predictions also indicated high quality sand in abundant volumes (37, 31, and 96 million cy, respectively) in these areas, but the potential threats to reef habitat from dredge activity and suspended sediment plumes should not be ignored.

Our model predictions also suggested that the nearer sand resource units DGS_42 (south and east of exhausted Maryland Borrow Area 9) and DGS_48 (Shoal R) may be promising sand sources barring any conflicting uses such as recreational fishing or protected habitat. These sand resource units were estimated to contain 54 and 37 million cy of sand, respectively. Our model predictions suggested additional sand resource units, DGS_49 and DGS_51, nearby with no corresponding shoal name in records that we could find. However, DGS_49 is small (0.24 million cy) and had a relatively low modeled sand quality score, making it an unattractive option. DGS_51 is larger (29 million cy), but it sits in a gap within BOEM's OCS Block Aliquots containing sand resources. It is close to suspected paleochannel deposits, which may limit its resource quality. DGS_50 (Shoal E), which sits between Isle of Wight Shoal and DGS_51, had an intermediate model score and estimated volume (12 million cy). There were several large resource units identified further out, but these conflict with offshore wind energy lease areas. Figure 3-7 illustrates the relative positions of these sand resources relative to known shoals and borrow areas. DGS_37 on this map corresponds to the Ocean City inlet ebb shoal. It is anticipated that beach nourishment of Assateague Island will be very infrequent if not non-existent in the long term, meaning competition for sand resource units south and east of Ocean City will be minimal. Conversely, all three major Delaware beach nourishment sites must rely on sand resources north of this area unless long distance south-north transport of sand becomes an option.

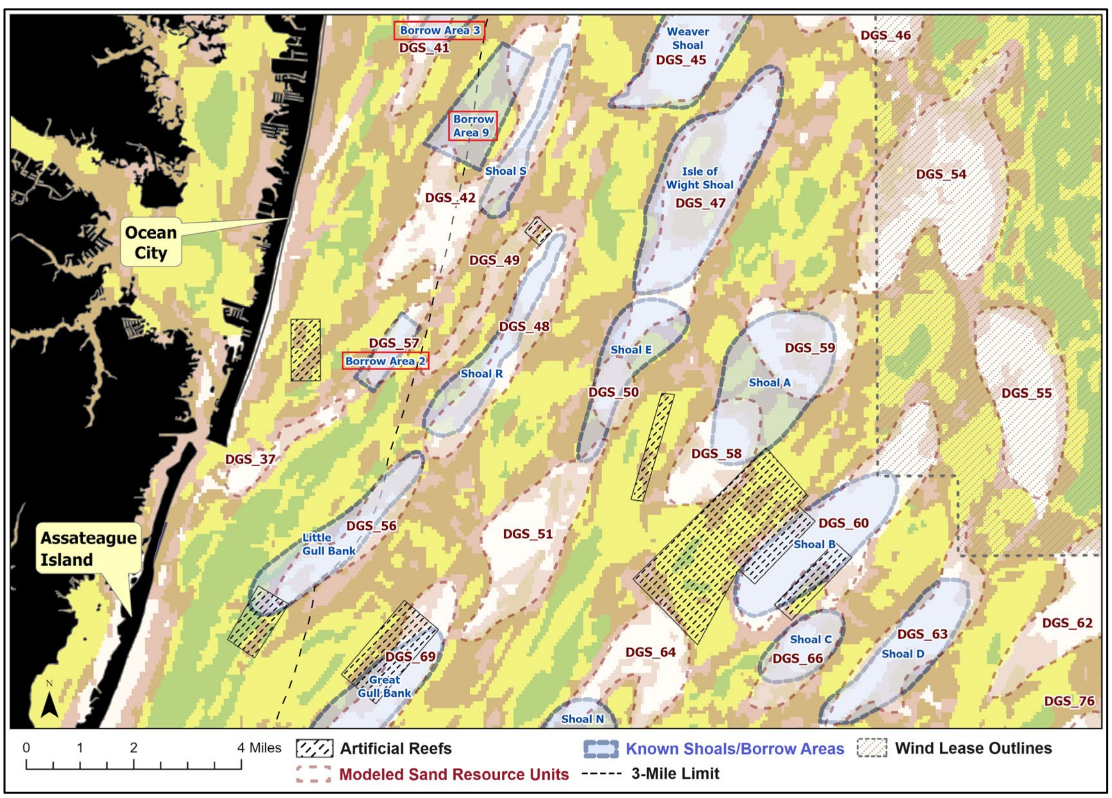

Figure 4-7. Overview of DGS-delineated sand resource units (red dashed lines) relative to known shoals and borrow areas (blue dashed outlines) off the Ocean City, MD coastline. Background colors correspond to modeled sand resource quality score classes as in Figure 3-2b. Also pictured are artificial reef boundaries (black dashed boxes) and boundaries for offshore wind energy lease zones (grey hashed box). Borrow area names in red boxes indicate discontinued borrow areas.

4.3.3.2 Future sand resources: Fenwick Island and Bethany/South Bethany, Delaware

Very few borrow areas east of the Delaware Atlantic coastline fall completely outside areas of potential MEC/UXO contamination. It is unknown if MEC/UXO are clustered in certain areas or where higher densities may be, and safety measures to address this issue will likely be a necessary complication for any offshore sand resource dredging projects in this area in the long term. For this reason, we do not place much weight on MEC/UXO risks in our recommendations within this region. Continued record keeping of encounters with MEC/UXO is necessary to better understand their spatial distributions and associated risks of exposure.

Fenwick Island and Bethany/South Bethany Beach currently use Delaware Borrow Areas F and E as sand sources. The proposed expansion of Borrow Area F (Fig 4-5; 4-8) east into DGS_40 and Borrow Area E south and north into DGS_39 may extend the effective lifetimes of these sand sources, though it is difficult to estimate by how long.

Closer to Bethany/South Bethany Beach is DGS_12 (Central Region Shoal; Fig 4-8) which had an estimated volume of roughly 11 million cy and a fair model prediction score. However, this sand resource unit intersects suspected paleo-channel deposits, which may reduce its resource quality. To the south of this is DGS_38, which scored well in our model output but has an estimated volume of only 3.8 million cy. Beyond DGS_12 lies DGS_26, which is estimated to contain roughly 47 million cy and had a moderately high model score. The drawback of DGS_26 is its distance from Bethany/South Bethany Beach. DGS_26 also sits beyond BOEM's OCS Block Aliquots containing sand resources.

Finally, Fenwick Shoal (DGS_33) and a smaller, heterogeneous area to the northeast with moderate model scores (DGS_34) together likely contain abundant beach quality sand. DGS_33 was considered as a sand source for Ocean City in earlier feasibility studies, but it was ultimately excluded due to potential MEC/UXO risks and potential interstate conflicts between Delaware and Maryland. It has the largest estimated volume of any sand resource unit within the study area at 184 (DGS interpolation estimate) and 211 (survey-based estimate) million cy, while DGS_34 has an estimated volume of 24 million cy. We assigned DGS_33 as a logical backup sand source for Fenwick Island once Borrow Area F is exhausted, but feasibility and environmental studies would be necessary before any action is taken to utilize it as a sand source.

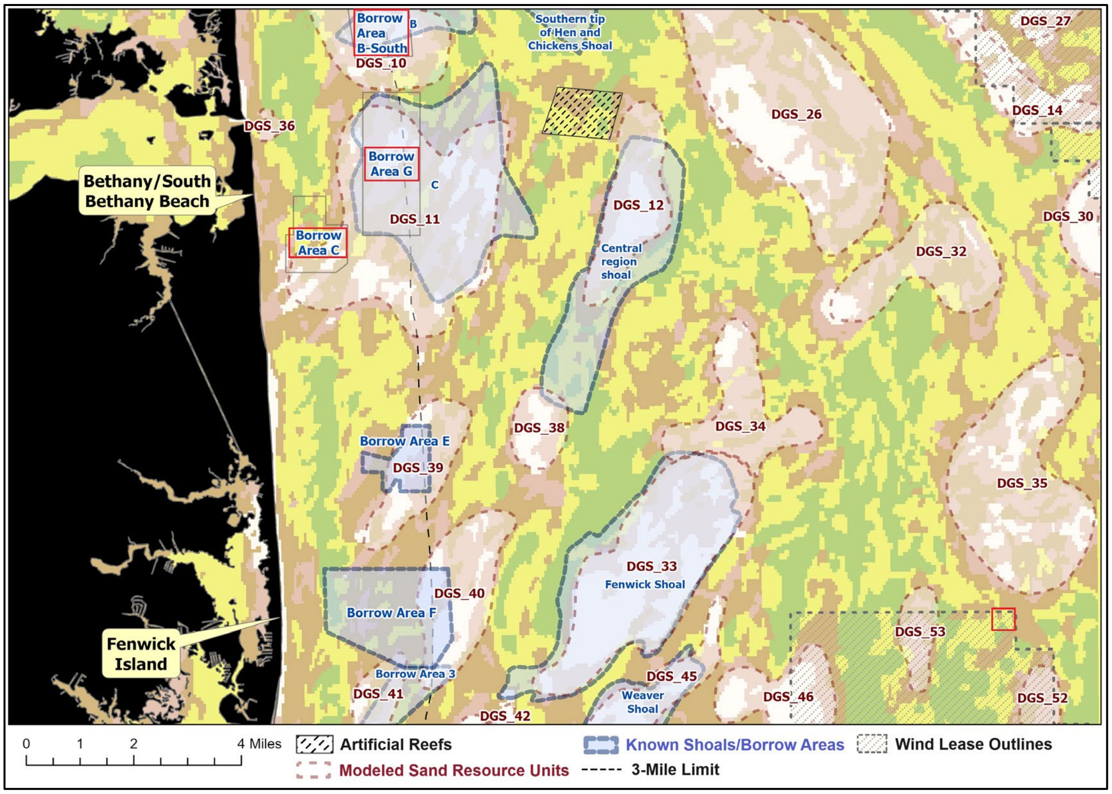

Figure 4-8. Overview of DGS-delineated sand resource units (red dashed lines) relative to known shoals and borrow areas (blue dashed outlines) off the Fenwick Island and Bethany Beach coastline. Background colors correspond to modeled sand resource quality score classes as in Figure 3-2b. Also pictured are artificial reef boundaries (black dashed boxes) and boundaries for offshore wind energy lease zones (grey hashed box). Borrow area names in red boxes indicate that they have been discontinued.

4.3.3.3 Future sand resources: Rehoboth and Dewey Beach, Delaware

The nearshore areas surrounding Rehoboth and Dewey Beach are a complex depositional environment where south-north longshore currents meet the mouth of Delaware Bay. Like Fenwick Island and Bethany/South Bethany Beach, most sand resource units here overlap with areas of potential MEC/UXO to some degree. Two large shoal structures, Hen and Chickens Shoal (DGS_1) and DGS_4 sit beyond a more heterogeneous seafloor environment of rippled sheet sands, small finger shoals, gravel beds, and muddy paleochannel deposits (Mattheus et al. 2020). DGS_1, DGS_4, and DGS_9 may contain very large volumes of beach quality sand. In fact, a portion of Hen and Chickens Shoal was used as a sand source for Dewey Beach long ago, but this was discontinued due to habitat concerns. In addition to habitat concerns, these large northern shoals also intersect areas with data transmission cables, and the other sand resource units east of them are on the other side of a major shipping lane, which could pose logistical challenges for beach nourishment activities (Fig 4-9).

However, finding suitable volumes of beach quality sand in the heterogeneous areas landward of DGS_1 has been an ongoing challenge. Borrow Areas G and B-South (DGS_10 and DGS_11) have both had issues by supplying overly coarse sand in the past. A proposed expansion of Borrow Area B into federal waters to the southeast falls within the same heterogeneous seafloor environment, which had low to moderate model scores. Cores in these areas indicate a mix of sediment qualities. Based on our model outputs and available core data, the benefits of expanding Borrow Area B are uncertain, and additional sand resources will still likely be needed in the mid-21st century.

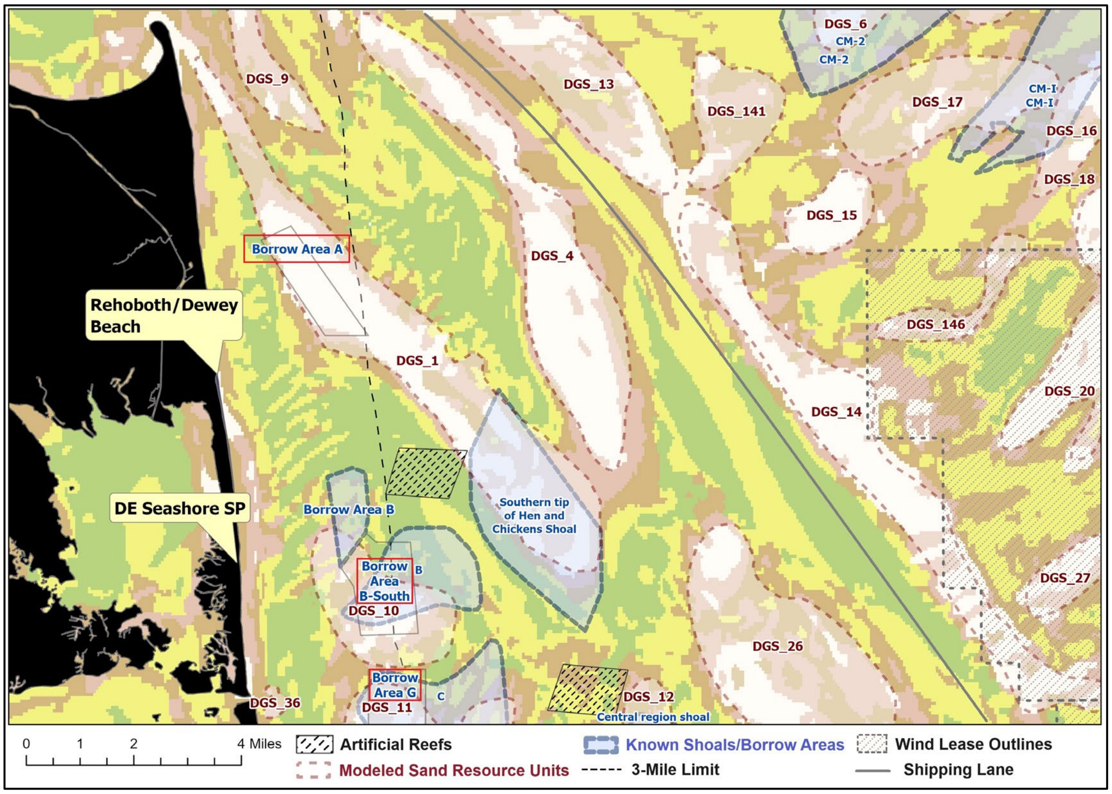

Figure 4-9. Overview of DGS-delineated sand resource units (red dashed lines) relative to known shoals and borrow areas (blue dashed outlines) off the Rehoboth and Dewey Beach coastline. Background colors correspond to modeled sand resource quality score classes as in Figure 3-2b. Also pictured are artificial reef boundaries (black dashed boxes) and boundaries for offshore wind energy lease zones (grey hashed box). Borrow area names in red boxes indicate that they have been discontinued. The solid grey line indicates the rough position of a major shipping channel.

5 Future directions and recommendations

Ocean City, Rehoboth/Dewey Beach, and Bethany/South Bethany Beach all needed new sand sources by 2100 under all forecast scenarios. Based on our forecasts and their associated assumptions, additional sand resources will be needed in the 21st century if beach nourishment is to continue as the preferred coastal stabilization approach. Further geological and ecological surveys to assess feasibility and environmental impacts of utilizing different sand resources are necessary, and we believe that this is a pressing need. Demand for space on the OCS is increasing, and early action to reserve promising sand resource units from conflicting interests will prevent resource sterilization in the study region.

Exactly when additional sand resources will be needed is less clear. Much hinges on the ability of Delaware's current borrow areas to supply quality sand without making dredge operations waste excessive time and effort searching for material. Both Borrow Areas B and E occupy heterogeneous seafloor environments, which may limit their usefulness as a sand source both in sediment quality and ease of dredging. If these borrow areas prove physically or logistically unviable, this will place substantially more demand on Borrow Area F or necessitate a shift to an alternative sand source. This issue is particularly acute for Rehoboth/Dewey Beach. Besides Hen and Chickens Shoal, which is one of the largest shoals in the study area, there are very few nearby options for sand sources of adequate volume to sustain the beach. As with any potential sand resource unit, the sand resource value of Hen and Chickens Shoal must be weighed against its ecological and recreational value in long-term coastal management plans.

An important avenue of future research is to improve our understanding of the ecological impacts both in dredging the seafloor and in placing new beach material. There is limited understanding of the long-term ecological impacts of the current approach of leasing borrow areas to be repeatedly utilized until a sand source is effectively exhausted. Looking to the future, especially in the S4 "worst-case" scenario, beach nourishments will become increasingly frequent, and this means that more borrow areas will be needed and ultimately exhausted. This will also shorten the ecological recovery time of both benthic and onshore habitats following the disturbance caused by dredging and sand placement. This could cause shifts in the biodiversity of both environments, as some species may recover more quickly from these disturbances than others. Strategies to reduce the ecological effects of frequent dredging may be needed, such as rotating sand sources to allow longer recovery periods for individual shoal systems. Similarly, alternative strategies like the "Sand Engine" in the Netherlands may reduce the frequency of dredging and the extent of sand placement disturbances (Stive et al. 2013). Though alternative approaches may seem radical and unpopular to coastal communities today, the current approaches towards sand resource management and beach nourishment may be logistically and economically infeasible under future sea level and climate regimes.

Based on the accumulated estimates of our forecasting simulations and offshore sand resource modeling, we submit the following recommendations for long-term sand resources planning within the study region.

- It is critical to continue sharing comprehensive records of beach nourishment volumes, sand source areas (including dredge tracking through DQM), field notes on sand resource quality and issues encountered, and environmental and economic assessments. This information is very useful for forecasting both sand needs and supply, and sharing this information between neighboring states and federal partners will support both long-term coastal management and OCS decisions.

- Additional offshore geological and ecological surveys are needed to characterize potential and unverified sand resource units. Geological sand characterization studies will verify the quality of sand within these units, while ecological surveys will identify which potential resources may be off limits due to habitat and/or environmental concerns. Conducting such surveys early on will help avoid potential OCS use conflicts and resource sterilization risks. Our analysis suggests that DGS identified shoals DGS_42, DGS_48 (i.e., Shoal R), DGS_12 (i.e., Central Region Shoal), DGS_38, DGS_26, DGS_1 (i.e., Hen and Chickens Shoal), and DGS_4 may be promising targets among others mentioned in Section 3.3.3.

- An eventual shift from nearshore (state-managed) sand resources to OCS sand resources is likely to occur in the coming decades. However, this shift will likely be staggered between different beach communities. Regional cooperation and planning between state, federal, and municipal stakeholders is necessary to avoid future resource conflicts. This is especially true in the Mid-Atlantic and Northeast regions, where there is a high density of beaches receiving periodic nourishments and municipalities across state lines may need to share sand resources.

- Echoing the recommendations of the USACE South Atlantic Division SAND report, the continued use of inlet ebb shoals and other potential BUDM sources when available will alleviate some of the stress placed on other dedicated sand resources. Similarly, studies of particle transport and settling after beach sand placement may help inform potential efforts to recycle placed beach sand lost to erosion.

- Begin early investigations into alternative beach nourishment strategies that may reduce the frequency of necessary beach nourishments. As erosive storm surge events become more frequent in the coming decades, more frequent beach nourishments may also be necessary. With this comes more frequent disturbances to the seafloor and beach habitat, demands for beach nourishment funds, and beach closures. Better understanding the economic and environmental impacts of increasingly frequent nourishment activities will also help guide long-term coastal management strategies for local and federal stakeholders.

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Appendix A: Sand resource units

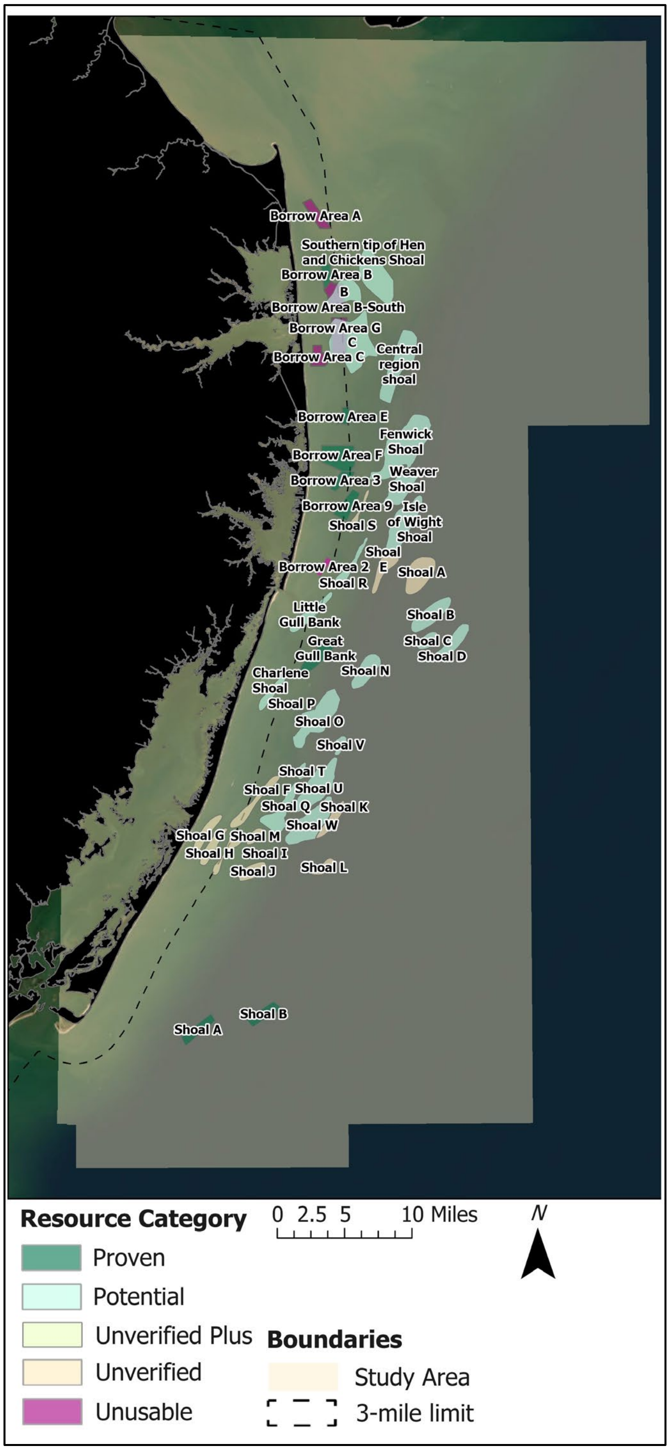

Figure A-1. Overview of known borrow areas and shoals from the BOEM Data Center. Borrow areas are categorized based on how well they have been characterized by core data, geophysical surveys, and past usage.

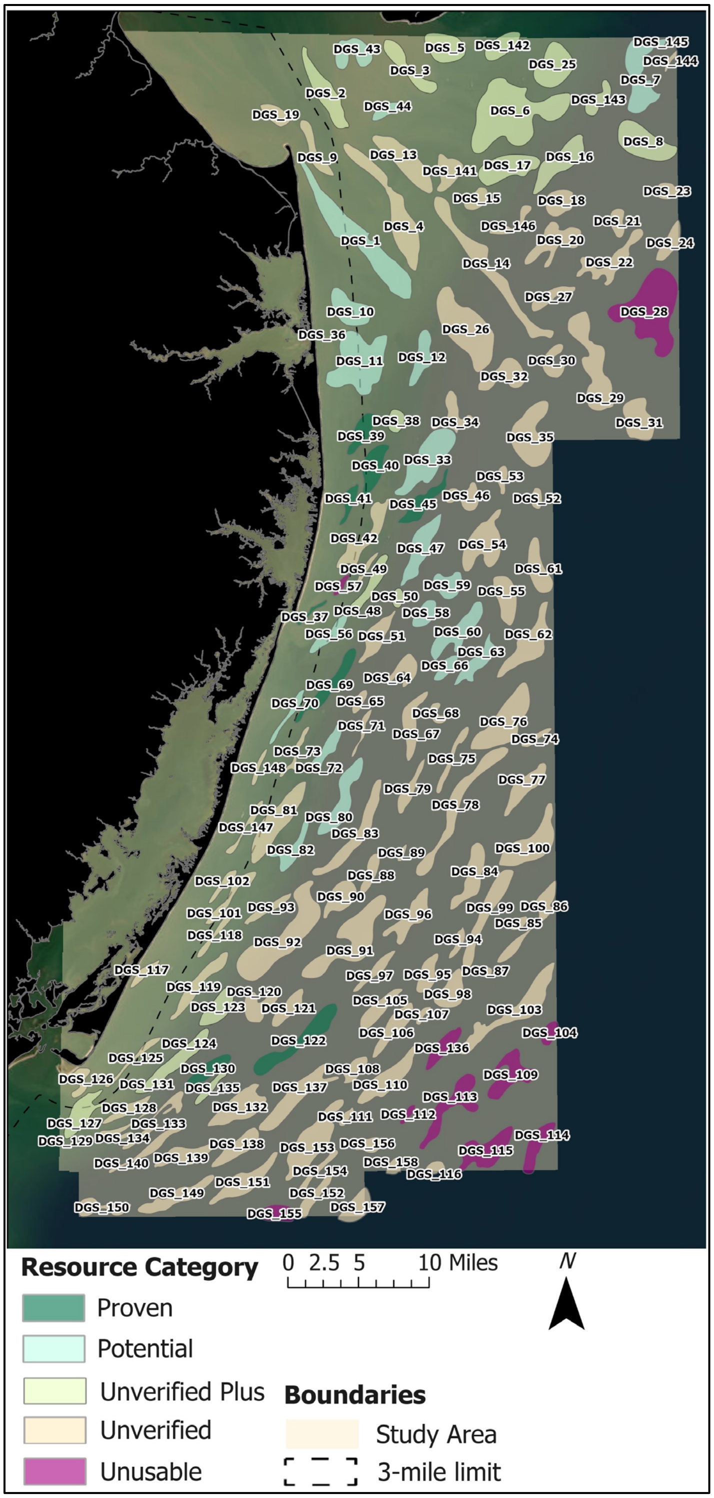

Figure A-2. Overview of delineated sand resource units from the DGS sand resource quality model. Borrow areas are categorized based on how well they have been characterized by core data, geophysical surveys, and past usage.

Table A-1. Overview of known sand resources and borrow areas within the study area. Estimated volume, current status, and past usages and issues are noted as well.

Managed By	Source Name	Source ID	Initial Volume (million cy)	Status	Past Usage	Issue
BOEM	**Great Gull Bank**	**BOEM_GG**	63	Discontinued	Assateague Island	Habitat
BOEM	**Isle of Wight Shoal**	**BOEM_IW**	136	Proposed	-	
BOEM	**Weaver Shoal**	**BOEM_WV**	93	In Use	Ocean City	
BOEM	**Fenwick Island Shoal**	**BOEM_FI**	211	Potential	-	Possible MEC/UXO
BOEM	**Shoal A**	**BOEM_A**	103	-	-	
BOEM	**Shoal B**	**BOEM_B**	50	-	-	Habitat
BOEM	**Shoal C**	**BOEM_C**	8	-	-	
BOEM	**Shoal D**	**BOEM_D**	24	-	-	
BOEM	**Shoal E**	**BOEM_E**	31	-	-	Too fine
BOEM	**Shoal F**	**BOEM_F**	55	-	-	
BOEM	**Shoal I**	**BOEM_I**	65	-	-	
BOEM	**Shoal J**	**BOEM_J**	63	-	-	
BOEM	**Shoal K**	**BOEM_K**	139	-	-	
BOEM	**Shoal L**	**BOEM_L**	72	-	-	
BOEM	**Shoal M**	**BOEM_M**	20	-	-	
Maryland	**Borrow Area 2**	**MD_B2**	-	Exhausted	Ocean City	
Maryland	**Borrow Area 3**	**MD_B3**	-	Exhausted	Ocean City	
Maryland	**Borrow Area 8**	**MD_B8**	-	-	-	
Maryland	**Borrow Area 9**	**MD_B9**	-	Exhausted	Ocean City	
Maryland	**Shoal G**	**MD_G**	23	-	-	
Maryland	**Shoal H**	**MD_H**	42	-	-	
Maryland	**Little Gull Bank**	**MD_LG**	50	Off Limits	-	Habitat
Maryland	**Charlene Shoal**	**MD_CH**	-	-	-	
Delaware	**Borrow Area E**	**DE_E**	25	In Use	Bethany/S. Bethany	Possible MEC/UXO
Delaware	**Borrow Area F**	**DE_F**	40	In Use	Fenwick Island	
Delaware	**Borrow Area G**	**DE_G**	90	Discontinued	Rehoboth/Dewey	Too coarse
Delaware	**Borrow Area B (North)**	**DE_BN**	11	In Use	Rehoboth/Dewey	
Delaware	**Borrow Area B (South)**	**DE_BS**	9	Discontinued	Rehoboth/Dewey	Poor quality
Delaware	**Hen and Chickens Shoal**	**DE_A**	-	Discontinued	Rehoboth/Dewey	Habitat