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WIND ENERGY SCIENCE DISCUSSIONS

Identification of Natural and Anthropogenic Hazards within Mid-Atlantic Bight For The Purpose of Offshore Wind Turbine Foundation Recommendations

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Abstract. The development of offshore wind energy in the Mid-Atlantic Bight is significantly influenced by the complex interplay of seabed topography, sediment characteristics, and human-made hazards. Utilizing seismic profiles and existing geological studies, this paper investigates the unique geological features and sediment types present in the region. These features include paleochannels, sand ridges, and varying sediment compositions, all of which have critical implications for the siting ~~and emplacement~~ of wind turbine foundations. The documented sediment types range from ~~fine~~ clays to coarser sands. Specific attention is given to glauconite sands in this research due to the unique challenges of their thixotropic behavior and potential to compromise ~~pile capacity during installation~~.

In addition to natural geological factors, human-made hazards—including unexploded ordnances (UXOs), shipwrecks, and artificial reefs, ~~are~~ barriers to offshore wind development. The presence of these hazards necessitates careful planning and may limit available space for turbine placement. Our findings emphasize the need for enhanced geotechnical assessments and innovative foundation solutions tailored to the unique characteristics of the seabed. Regulatory frameworks that adapt to evolving understandings of seabed conditions and hazard mitigation strategies are needed to ensure the safe and efficient installation of offshore wind turbines. Ultimately, a comprehensive understanding of both natural and human-made hazards is crucial for the successful development of offshore wind projects in the Mid-Atlantic Bight to balance the economic and energy benefits against the complexities of the marine environment.

1 Introduction

Barriers to the siting and emplacement of wind turbine foundations can be categorized into anthropogenic and natural hazards. Anthropogenic hazards include unexploded ordnances (UXOs), artificial reefs, shipwrecks, and vessel navigation pathways. According to Bureau of Ocean Energy Management (BOEM) regulations, these hazards must be avoided, which prevents the installation of wind turbines in these areas (BOEM, 2024). While natural hazards do not necessarily eliminate siting possibilities, they may complicate the process and should be avoided where possible. These natural hazards include unsuitable sediment types, steep slopes, paleochannels, and enhanced bottom sediment transport. Engineering solutions can mitigate the risks posed by many of these hazards.

2 Background

2.1 Location

The study area includes two designated offshore wind energy areas within the Mid-Atlantic Bight: Call Area A and Call Area B, both part of the broader Central Atlantic Call Area 1 established in 2022 (BOEM, 2022) -Shown in Figure A1. These regions lie on the U.S. outer continental shelf within a strategic corridor for Mid-Atlantic offshore wind energy development. Call Area A, spanning approximately 235,554 acres, extends from 74.6563749°W, 38.4794873°N at its westernmost point to 74.3332031°W, 38.7096248°N at its easternmost point. Farther south, Call Area B covers a more extensive 687,119 acres, ranging from 75.0173971°W, 37.0789779°N at its westernmost boundary to 74.5128573°W, 38.1961733°N at its easternmost edge. Call Area B's broader expanse presents diverse subsurface features that warrant comprehensive geological and geotechnical assessment for potential wind turbine foundation planning.

Each area presents unique geological features which are crucial factors in seabed stability and offshore wind foundation suitability. Together, Call Areas A and B offer complementary insights into the geological variability across Central Atlantic Call Area 1, supporting the evaluation of optimal locations for offshore wind turbine foundations.

2.2 ~~Seafloor Geology~~

The submarine topography of the Mid-Atlantic Bight, including the Central Atlantic Call Area, is characterized by several distinct seabed features. As identified by Swift (1975), these include valleys with intervening shoals, scarps, sand ridges, and marine cuestas (i.e., asymmetric ridges with a gentle back slope and a steeper front slope). Surficial sediments range from ~~fine~~ clays (mud) to sands to ~~small~~ gravels, with the surficial sediment primarily consisting of sands (Anderson et al., 2010). Closer to shore, there is more mud, whereas the outer continental shelf ~~contains~~ more sand. Studies of the shallow subsurface sediments off the coasts of Delaware, New Jersey, and the Delmarva Peninsula (Brothers et al., 2020; Mattheus et al., 2020; Lofi et al., 2013) have mapped the formations of Tertiary, Quaternary, and more recent Holocene-age sediments. Many of these sediment deposits occur throughout the subsurface of the Mid-Atlantic Bight and are often associated with paleochannels or buried ancient riverbeds (Brothers et al., 2020). These formations are discussed on Table A1.

3 Methods

3.1 Geological and Bathymetric Data Collection

Data for the assessment of seabed hazards in the Mid-Atlantic Bight were gathered from multiple agencies and studies. National Oceanic and Atmospheric Administration (NOAA) provided bathymetric information and identified surficial sediments (Anderson et al., 2010), while the United States Geological Survey (USGS) contributed insights into surface and subsurface sediment characteristics (USGS, 2013). The Delaware Geological Survey (DGS) and the International Ocean Discovery Program (IODP) added coring data, which was instrumental in understanding sediment layers (Mattheus et al., 2020; McInroy et

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al., 2010; Lofi et al., 2013). Wind energy companies, such as US Wind, Ocean Wind, Skipjack, and GSOE I LLC, performed extensive geological surveys that helped identify paleochannels offering insights into subsurface sediment layers (McNeilan, 2023; Stantec, 2019). These paleochannels are important for wind turbine foundation assessments due to their heterogeneous fine grained sediments and variability in the sediment layers. Additionally, BOEM provided data on glauconite sands, a significant sediment type in the Mid-Atlantic region (Bruggeman et al., 2023).

3.2 Geospatial and Seismic Reflection Surveys

The data from the aforementioned sources were integrated into geospatial analyses using Geographic Information Systems (GIS) to map hazards across the proposed offshore wind energy areas (WEAs). Existing seismic reflection surveys (CB&I, 2014) were included to map subsurface features such as paleochannels and sediment formations. These surveys provided a detailed view of the subsurface geology, which is crucial for understanding sediment stability and the risks associated with subsurface formations. Core sampling and grain-size analysis conducted by (Mattheus et al., 2020; McInroy et al., 2010; Lofi et al., 2013) were used to determine sediment properties, such as shear strength and porosity, which influence the stability of turbine foundations.

3.3 Sediment Movement and Storm Impacts

Studies by Bianucci et al. (2018) and Dietz et al. (2021) were referenced to analyze bottom sediment movement in response to coastal storms and slope activity. This analysis helped assess the risks posed by sediment mobility, particularly caused by high-intensity nor'easters and hurricanes. Bottom currents, storm-induced sediment movement, and the influence of paleochannels on sediment distribution were critical factors considered in assessing natural hazards in the region.

3.4 Anthropogenic Hazards

The evaluation of anthropogenic hazards focused on ~~barriers such as~~ unexploded ordnances (UXOs), artificial reefs, and shipwrecks. Remote sensing techniques, including side-scan sonar and magnetometer surveys, were employed to detect these objects ((NOAA, n.d.)). UXOs and shipwrecks pose significant risks to offshore wind infrastructure, and their locations must be accounted for during site planning. Additionally, maritime traffic data was used to evaluate risks from vessel collisions. Automated Identification Systems (AIS) and Coast Guard data sets were utilized to map vessel traffic density and major navigation routes within the WEAs (Fonenault, 2024; Coast Guard, 2020).

3.5 Hazard Compilation and Risk Ranking

Once the geological and anthropogenic data were collected, they were compiled into a comprehensive hazard list detailing the seabed's features, sediment types, and the locations of potential hazards. Areas with unstable sediments, high sediment mobility, or concentrations of UXOs were flagged for further risk assessment. Each hazard was ranked based on its potential impact on wind turbine infrastructure, with particular attention given to regions with intersecting paleochannels or high sediment mobility (Table A2).

3.6 Mitigation Strategies and Validation

Mitigation strategies were proposed based on the identified hazards, with a focus on ensuring the safety and stability of offshore wind projects. Engineering feasibility studies explored mitigation options, such as alternative foundation designs and scour protection measures, especially in areas where paleochannels or high sediment mobility posed risks. These strategies were validated through evaluating regulatory agencies' documents from BOEM, the USGS, and the U.S. Coast Guard (BOEM, 2024; Coast Guard, 2020). The evaluations ensured that the mitigation measures complied with safety and regulatory standards while addressing the unique challenges of the Mid-Atlantic Bight.

4 Anthropogenic Hazards

Offshore wind energy development in the Mid-Atlantic Bight encounters several human-made hazards that should be considered. In Section A, an artificial reef has been identified and would need to be avoided (ASMFC, 2021). Section B presents the risk of UXOs, with one known UXO location, though further exploration during seismic data collection is required to confirm if more are present (NOAA, n.d.). For instance, US Wind reported discovering a few UXOs during their geotechnical survey despite previous government reports indicating none in the area (CB&I, 2014). Additionally, there are numerous shipwrecks within the call areas—25 in Section A and nine in Section B—making these zones either unsuitable for wind turbine construction or necessitating costly removals (ssorens2, 2019). While BOEM considered major navigation routes when designating the call areas, a vessel navigation fairway still runs through Section B, currently under review for approval (Wagner, 2021; Coast Guard, 2020). This area may need to be excluded from development to ensure safety. Identifying and mitigating these human-made hazards is essential to secure the success of offshore wind energy projects and protect industry workers.

5 Natural Hazards

5.1 Sediment Type

Each wind turbine foundation type (e.g., monopile, suction caisson, gravity base, and jacket) has specific geotechnical requirements largely determined by the surface and subsurface sediments present. Different sediment types exhibit distinct properties, ~~including shear strength, expansion or shrinkage~~, compressibility, and permeability. For example, inorganic clays have low shear strength, ~~expand when wet~~, and are highly compressible, while ~~inorganic silts have low shear strength, low permeability, and are difficult to compress~~. ~~These finer-grained sediments can behave differently depending on their water content, known as the plasticity index—the more water present, the weaker and more fluid-like the sediment becomes. Coarser sediments, like sand and gravel, have higher permeability. The stress on saturated sediments consists of intergranular stress and pore water pressure (Verruijt, 2001)~~.

The Mid-Atlantic Bight's continental shelf features alternating layers of sand, silt, clay/mud, and gravel, which vary in location due to the transgression and regression patterns caused by sea level changes. These patterns can be traced through seismic profiles and correlated with known formations and paleochannels which helps to predict sediment locations and reduce costs in geotechnical exploration. Key sediment properties such as void ratio, porosity, degree of saturation, and moisture content influence the behavior of sediments. ~~These characteristics can be determined from the unit weight and volume of a sediment sample compared to its relative density.~~ While most sediments are considered fully saturated, marine ~~organics~~ may cause gas accumulations, leading to combination soil profiles and altering sediment properties (Meehan, 2023).

Saturated sediments display properties specific to their material composition, such as quartz or carbonate sand, which influence both friction and water interactions(Verruijt, 2001). ~~In combination with soil profiles, the characteristics of any air present also affect the sediment's void ratio and density, which in turn influence its strength and the normal (vertical) and shear (lateral or horizontal) stressors.~~ The moisture content of the sediment also affects its stiffness and compressibility: loose, soft sediments compress, creating positive pore pressure; inversely, dense, stiff sediments dilate, creating negative pore pressure. This relationship is especially important for finer-grained sediments like clay, which may be over-consolidated(Horslev, 1961; Meehan, 2023).

Finer-grained sediments present further complexity due to unique properties measured by Atterberg limits, including liquid limit, plastic limit, ~~and plasticity index.~~ These require more detailed and costly testing compared to coarser-grained sediments like sand or gravel. Many projects conduct only minimal testing to save money, which can lead to ~~less accurate geotechnical assessments for fine-grained soils like clay, mud, or silt.~~

~~When assessing foundation stability in these sediments, the primary concern is how loading will affect the stress on the sediment. Horizontal and vertical loads exert shear and normal stress, respectively, on the foundation. These stresses determine lateral stress, calculated by the equation~~

~~$ph = [v/(1-v)] * po$~~ ~~(1)~~

~~where v is the ratio between lateral (shear) and vertical (normal) strains, and po is the weight of the soil layer above the desired depth. This equation helps establish the depth of significant influence (DOSI), indicating how deep a structure must be placed to remain stable. For sediments such as sand or gravel, the ratio would range between 0.25 and 0.35, while saturated clays under rapid loading conditions would be closer to 0.5 (Verruijt, 2001).~~

Uni~~que~~ sediment types, such as glauconite sand, present specific complications. According to a BOEM study, glauconite sand, or "green sand," poses a geotechnical hazard for offshore wind turbines due to its behavior when pile-driven. Glauconite, a mineral formed in shallow marine or lagoonal environments during the Cretaceous to Paleogene periods, often occurs at this boundary and can form layers up to 50 feet thick((Miller, n.d.)). As glauconite ages, it transitions through four phases, becoming more clay-like and stable unless disturbed by changes in sea level. In its unstable state, under stress, the mineral's shear strength decreases and plasticity increases, much like clay. This phenomenon, known as thixotropy, occurs when shear resistance diminishes with increased shear rate. ~~In saturated conditions, typical of the Outer Continental Shelf, thixotropy can cause the sediment to liquefy, behaving like quicksand due to reduced grain contact.~~ This thixotropy and the crush-ability

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of glauconite sand pose significant concerns for offshore wind turbines, as it may result in high driving resistance or excessive friction during monopile installation~~, reducing pile capacity with depth~~ (Bruggeman et al., 2023). According to George Hagerman from DENREL, glauconite sand becomes sticky and plaster-like when pile-driven (Westgate et al., 2022).

5.2 Sediment Movement

When installing offshore wind turbines, developers should consider the long-term stability of their projects, typically designed to last 30 years (DOE, n.d.). One critical factor in this is sediment movement, which can affect the turbine foundations over time, particularly through a process known as scouring—the movement of sediment around the base of the turbine (Hughes, n.d.).

Sediment movement can originate from several sources, including sedimentation, sediment transport, turbidity currents, and bottom currents. Sedimentation adds between 0.1 and 1 cm of sediment per year, which, over time, can impact turbine foundations, particularly in areas with higher sedimentation rates ((Trujillo, n.d.)). Sediment transport varies based on the size and source of the sediment.

Turbidity currents can re-suspend sediment from deeper waters, with sediment movement occurring up to 90 meters underwater (Bassetti et al., 2022). Bottom currents along the continental shelf typically flow at speeds of around 20 cm/s but increase in velocity as they approach the continental slope (Csanady et al., 1987). Therefore, The outer edges of Call Area B would be affected by this. Storms can further enhance bottom current speeds, leading to significant sediment displacement.

5.2.1 Coastal Storms and Earthquakes

The Eastern U.S. Continental Shelf is a storm-dominated autochthonous shelf, which means plentiful sediment movement occurs during storm events, particularly hurricanes and nor'easters. Hurricanes and their associated waves can cause powerful water column movement, re-suspending large volumes of sediment from the continental shelves. The intensity of the storm determines the extent of sediment displacement, with some hurricanes capable of moving up to a meter of sediment (Bianucci et al., 2018). The direction of the storm also influences sediment transport. When a storm moves landward, lighter oceanic sediments are carried toward the coast, while a seaward-moving storm can transport terrestrial sediments, including fluvial materials, out into the ocean. These events can form new sediment layers, which are important for studying modern storms and improving paleo-hurricane predictions (Dietz et al., 2021). Nor'easters, which frequently hit the Mid-Atlantic Bight, can also cause sediment displacement.

Major storms, such as Hurricane Sandy, have been studied for their impact on sediment movement along the Eastern U.S. coastline. For example, research conducted north of Delaware Bay found around 3 cm of sediment deposition following Hurricane Sandy, with the sediment primarily consisting of very fine sand (0.1 mm) but also moving coarser particles (Bever et al., 2015). Hurricanes play a significant role in shaping the seabed, both by re-suspending sediments and by depositing new layers, which can alter the marine environment and potentially affect the stability of offshore structures. Noreasters can also impact these marine environments. For example, during a January 2016 storm, the Red Bird Reef off the coast of Delaware, a structure 51 feet long and 9 feet wide, was rotated 160 degrees, and many other artificial reefs were turned on their sides (Murray, 2016).

Additionally, other major events, such as earthquakes, contribute to sediment movement. While earthquakes are more frequent on the Pacific coast, the Mid-Atlantic Bight faces its own risks, with a fault zone off the coast of New Jersey posing a threat to sediment stability (Booth et al., 1983). Minor seismic activity could destabilize sediments, especially in areas of mud or clay, causing ground accelerations, excess pore pressures, or slope instability (Verruijt, 2001). These events underscore the importance of understanding sediment movement when planning offshore wind projects.

5.3 Paleochannels

5.3.1 Call Area A

~~Paleochannels not only affect the surficial sediments but can impact subsurface sediment movement along the buried river (Verruijt, 2001). These channels can create high bottom current flow (McNeilan, 2023).~~ Due to the heterogeneity of their infill sediments, two paleochannels adjacent to the southwest edge of Call Area A pose challenges to the siting and design of turbine foundations in this portion of the WEA. These paleochannels trend from the Delaware Bay southeast towards the outer shelf, which links either with the Wilmington Canyon (Twitchell et al., 1977) or the Baltimore Canyon (Murphy et al., 1996; Krantz et al., 1993; Childers, 2014). Based on cross-cutting relationships, the further eastern paleochannel, identified as the blue channel by (Murphy et al., 1996; Childers, 2014), is younger than the more southern orange channel (Murphy et al., 1996; Childers, 2014). The sediments within the blue channel as deep as 63 m filled in as the Holocene transgression began approximately 14,000 years ago and continued until about 7,000 years ago. However, the older orange channel may go back as far as the beginning of the late Pleistocene (60,000 to 30,000 years ago) to the last glacial maximum within the Pleistocene. The orange and blue channels likely have attributes of the late Wisconsinan era characteristics (Childers, 2014).

To the north of Call Area A, two additional large channels and one smaller channel have been mapped (Childers, 2014). These channels have been identified, from west to east, by several authors, including (Childers, 2014; Belknap and Kraft, 1985; McGeary et al., 1991; Krantz et al., 1993, 1994) as the yellow, green, and red channels. The yellow channel, with a width of 700–1000 m and a depth of 17–21 m, may be a tributary of the blue channel, though it does not connect to any nearby channel to confirm its age (Childers, 2014). The green channel is thought to consist of mid-Pleistocene material, possibly from the Omar Formation, as discussed by (Ramsey, 1999; Groot et al., 1990; Childers, 2014). It is the second oldest channel, with a gradient of 0.4 m/km. The red channel is the oldest, potentially infilled during the Pliocene and associated with the Beaverdam Formation. This channel has been referenced in previous literature (Gill, 1962; Lacovara, 1997) and further analyzed in (Childers, 2014). The contact between the Omar and Beaverdam formations changes in depth near the point where the orange and blue channels diverge and enter Call Area A. Within this area, the depth ranges from approximately 40 to 75 m, which trends deeper toward the eastern shelf. However, this data was analyzed only up to approximately 74° 30′ W (Childers, 2014).

5.3.2 Call Area B

As discussed in the Formations section, several paleochannels run through Call Area B, which includes the Cape Charles, Eastville, Exmore, Persimmon Point, and Ocean City paleovalleys, each with associated tributaries. In the study by Brothers et al. (2020) on the Delmarva Peninsula, they analyzed the infills of transgressive system tracts (TST). Based on multiple sets of bathymetric data and the findings from Brothers et al. (2020), these paleochannels are significant features which influence sediment composition and foundation characteristics in the area.

The Q3/Qcch paleochannels, similar to the Williams (1999) paleochannels shown in A2, exhibit complex pathways due to the intricate barrier systems along the East Coast, particularly near Ocean City and Assateague Island (Brothers et al., 2020; Childers, 2014). These smaller channels run through the WEA of US Wind. It is probable that the paleochannels identified in the Williams (1999) study and Toscano et al. (1989) seismic lines (Q3) form complex connections beneath the seabed and contain finer clays.

Brothers et al. (2020), categorize these paleochannels by their deposition order and ancestral riverbeds. Outside of the paleochannels, sand dominate the seafloor landscape. At the base of each paleochannel, coarser materials like larger sediments or rocks are commonly found, which contrasts with the finer sediments that fill the channels. The Cape Charles Paleochannel, for instance, is the ancestral riverbed of the Susquehanna River, which contains river, tidal, back-barrier, and other Quaternary sediments. Beneath it lies the Eastville Paleochannel, which represents the historical base of the York/James River. The Exmore and Belle Haven paleochannels, which have similar sediment infill, are believed to be tributaries of the ancestral Rappahannock River.

Beneath these formations lies infill from the Beaverdam Formation, which likely marks the boundary between the Pleistocene and Pliocene (Tertiary sediments). Additionally, two older Tertiary paleochannels, identified as Tchy and Tchb, have not been linked to specific ancestral rivers. Below these paleochannels, even older Neogene sediments are present (Brothers et al., 2020). Further details on these formations are provided in Table A1.

The depth to the Neogene sediments is a critical factor to locate the depth of the paleochannels and the characteristics of the overlying formations that would affect offshore projects. According to Brothers et al. (2020), as one moves seaward, the depth to the Neogene sediments increases. In areas with paleochannels, this depth is even greater than in the surrounding regions. The Exmore paleochannel, for example, shows the largest depth to the Neogene sediments, which reach approximately 80 meters (Brothers et al., 2020).

6 Discussion and Future Areas of Research

6.1 Seabed Complexity and Turbine Installation Challenges

The study highlights the importance of understanding the Mid-Atlantic Bight's seabed formations, which include paleochannels, sand ridges, and varying sediment types. These features impact wind turbine foundation ~~stability.~~ Identifying areas with steep slopes or unstable sediment formations, such as sand ridges and paleochannels, helps avoid turbine placement in risky locations. Engineering solutions, such as enhanced foundation types or additional ~~sediment studies~~, may be necessary to stabilize turbines in these areas.

6.2 Sediment Properties and Foundation Stability

Sediment characteristics such as shear strength, permeability, and compressibility vary across the Mid-Atlantic Bight, influencing the choice of foundations for wind turbines. Coarse sands, for example, offer better stability compared to clays~~, which may weaken due to saturation and compaction~~. While the thixtotropic properties of glauconite sand can reduce pile capacity and affect monopile installations. ~~These unique sediment strengths create a need for geotechnical innovations when dealing with sediments prone to liquefaction under stress.~~

Clays over non-carbonate sands provide a stable base for the construction of monopile foundations. However, they face challenges in regions where sand overlies clay, particularly within paleochannels, which can lead to foundational instability. Suction bucket foundations perform well in locations with sand over a clay layer but are less effective in areas with clay over sand, stiff clays, or gravels, which compromise their ~~anchoring efficiency~~. Gravity base foundations are ideal for sands and coarse gravels, providing robust support, but struggle in muds or clays where dredging may be required to establish a stable base. Jacket foundations are highly adaptable and capable of being used in most sediment types, but they can encounter problems in areas with paleochannels or steep elevation changes that complicate installation.

According to BOEM, 24% of the sediment deposited during the Paleogene contains glauconite, suggesting it is widespread across the Outer Continental Shelf (Bruggeman et al., 2023). Few effective solutions have been developed to address the challenges posed by glauconite. One option is to exclude affected areas from wind farm development, but this can negatively impact the project's power output goals. Belgian researchers have had success addressing glauconite in river environments by pre-drilling with an auger, which improved pile-driving results (Bruggeman et al., 2023). Another technique, known as the "drill-drive-drill" or relief drilling method, involves periodically stopping the hammering process to clear ~~mud~~ from the monopile using a drill (Westgate et al., 2022). ~~Whether monopile driving is feasible depends on the depth of the glauconite sand, due to the depth of the drill.~~

Glauconite formation, which occurred from the late Cretaceous through the Paleogene (65.5–23 million years ago) ((Miller, n.d.)), suggests that, based on Brothers et al. (2020), glauconite sand at a 15 m water depth would have formed at 30 m or more below the seafloor. Given that suction caisson foundations require less than 25 m of penetration into the seafloor (Cotter, 2009), they could be a viable alternative. Suction caisson testing on glauconite sand is already underway in the Beacon Wind project (Richards, 2024). Ultimately, the complexity and costs of addressing natural hazards like glauconite must be carefully weighed against the economic and energy benefits of offshore wind development.

6.3 Natural Hazards and Sediment Movement

The study discusses natural hazards like storms and earthquakes, to emphasize their role in sediment movement. Coastal storms, particularly hurricanes, affect sediment displacement, which can alter seabed topography and, in turn, impact turbine stability over time. The potential movement of sediments around turbine foundations through scouring and re-suspension poses long-term risks to the structural integrity of offshore wind farms. Storms, like Hurricane Sandy, can deposit or erode sediments, creating unpredictable seabed conditions.

6.4 Paleochannels and Subsurface Sediment Impact

Paleochannels, dating back to the Pleistocene and earlier, strongly influence sediment dynamics in the Mid-Atlantic Bight, impacting both surface and subsurface sediment movement. Assessing the depth and composition of these ancient river systems is crucial for determining foundation stability, as they may require specific geotechnical evaluations to address potential sediment shifts.

At the Beaverdam/Omar formation boundary, paleochannels often contain finer-grained sediments that could challenge foundation stability. However, seismic mapping of channels across the continental shelf, especially in Call Area A, remains incomplete. Bathymetric analysis shows that paleochannels direct sediment flows toward major underwater canyons: the orange and blue channels flow toward Baltimore Canyon (near 37.9°N), while the red channel heads toward Wilmington Canyon (near 38.2° N). The yellow channel likely merges with the green, which connects with the blue channel, directing sediment toward Baltimore Canyon.

In Call Area B, bathymetric data and findings from Brothers et al. (2020) suggest paleochannels, like the Cape Charles and Eastville channels, flow toward Norfolk Canyon (near 37°N latitude), while Exmore and Persimmon Point channels are likely directed toward Washington Canyon (around 37.5°N). Smaller channels found in the Williams study likely connect to Accomac Canyon (near 37.85°N) within Call Area B, although shallow and abundant channels make precise mapping difficult. Northern paleochannels, possibly connecting to the blue channel, appear to flow toward Baltimore Canyon, as shown in Figure A2. Detailed bathymetric mapping of these paleochannels is essential to understand sediment movement and ensure the stability of offshore wind structures. Knowledge of local geological formations helps guide engineers on expected sediment types, aiding site evaluation before geophysical investigations.

6.5 Anthropogenic Hazards as Obstacles to Development

Human-made hazards such as UXOs, shipwrecks, and artificial reefs are critical barriers that must be avoided during wind farm planning. These hazards either increase the cost of development (e.g., through removal or mitigation efforts) or limit available space for turbine installation. The presence of vessel navigation routes further complicates siting, especially in areas with existing shipping lanes.

6.6 Geopolitical and Regulatory Implications

BOEM regulations, along with ongoing research into both human-made and natural hazards, highlight the complexity of offshore wind development. Regulatory frameworks should evolve alongside advances in understanding seabed conditions and hazards to ensure safe and efficient wind turbine installations. Many developers' Construction Operations Plans typically propose monopiles as the preferred foundation. However, BOEM could require risk mitigation strategies specific to the chosen foundation, with justification for the selection. Furthermore, the presence of unexploded ordnances (UXOs) and artificial reefs introduces legal and logistical challenges that could delay development if not properly addressed.

7 Conclusions

The Mid-Atlantic Bight presents a variety of natural and anthropogenic hazards that complicate the development of offshore wind energy. Understanding the involvement between seabed topography, sediment types, and subsurface formations is critical to selecting optimal locations for wind turbines. Natural hazards, particularly sediment movement caused by storms, introduce long-term risks to turbine stability, while human-made hazards, like UXOs and shipwrecks, create additional barriers that increase the complexity and cost of development. These hazards' severity and how to progress forward are detailed on Table A2.

Innovative engineering solutions are necessary to mitigate these risks, particularly in areas where natural hazards, like paleochannels or unstable sediments, cannot be completely avoided. Additionally, regulatory frameworks must evolve to manage both the natural and human-made challenges in the region. For successful offshore wind energy projects, it is essential to balance the technical, economic, and environmental considerations, ensuring that these hazards are effectively managed to promote long-term stability and safety.

Data availability. All data used in this study are publicly available and have been properly referenced throughout the manuscript. Specific datasets and their sources can be found in the references section. Readers are encouraged to consult these references for further details on the data utilized in this research.

Sample availability. The geotechnical data mentioned is referenced in the manuscript, with additional core data sourced from the Delaware Geological Survey (DGS)(Mattheus et al., 2020), the National Oceanic and Atmospheric Administration (NOAA)(Anderson et al., 2010), the International Ocean Discovery Program (IODP)(McInroy et al., 2010), and New Jersey subsurface surveys(Lofi et al., 2013). These sources provide further context and detail regarding the data used in this research.

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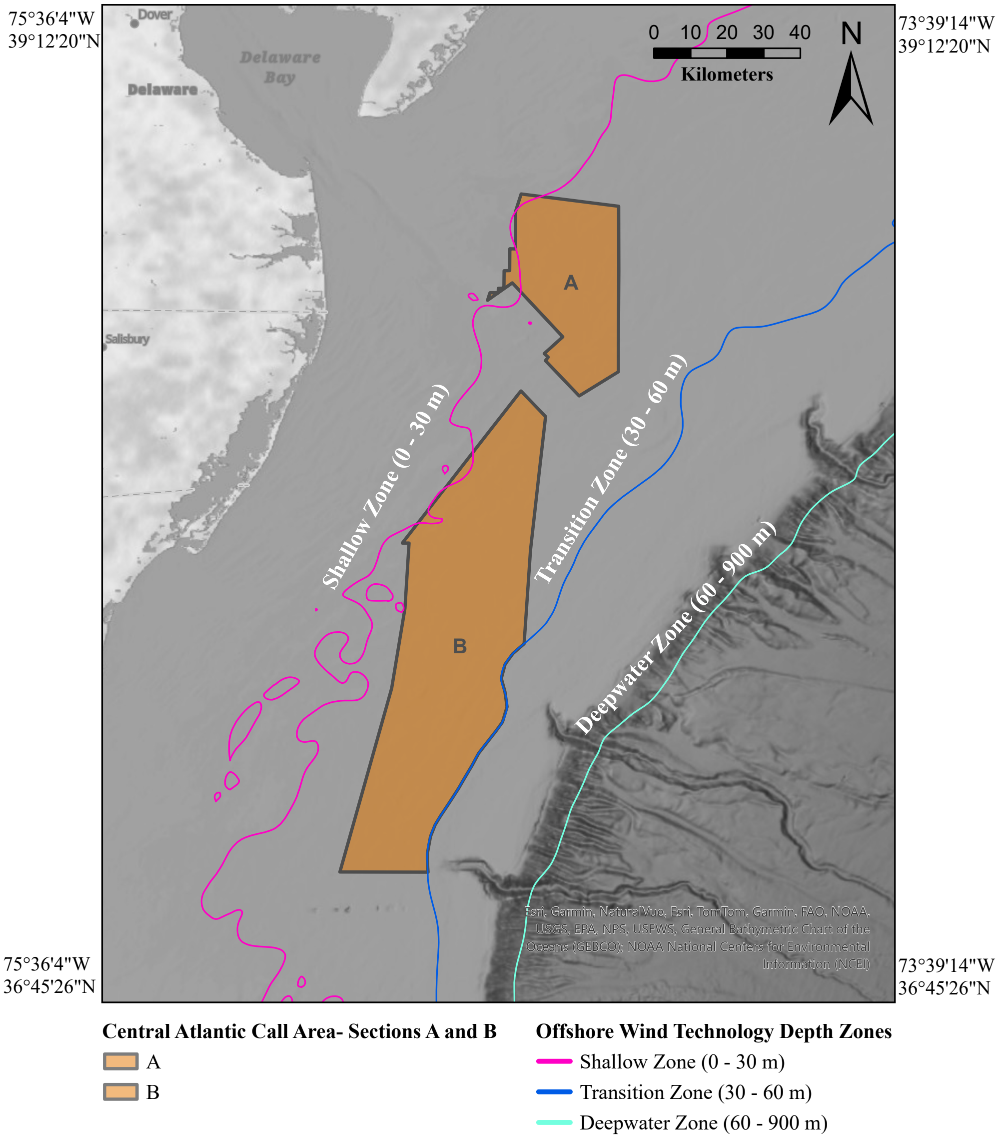
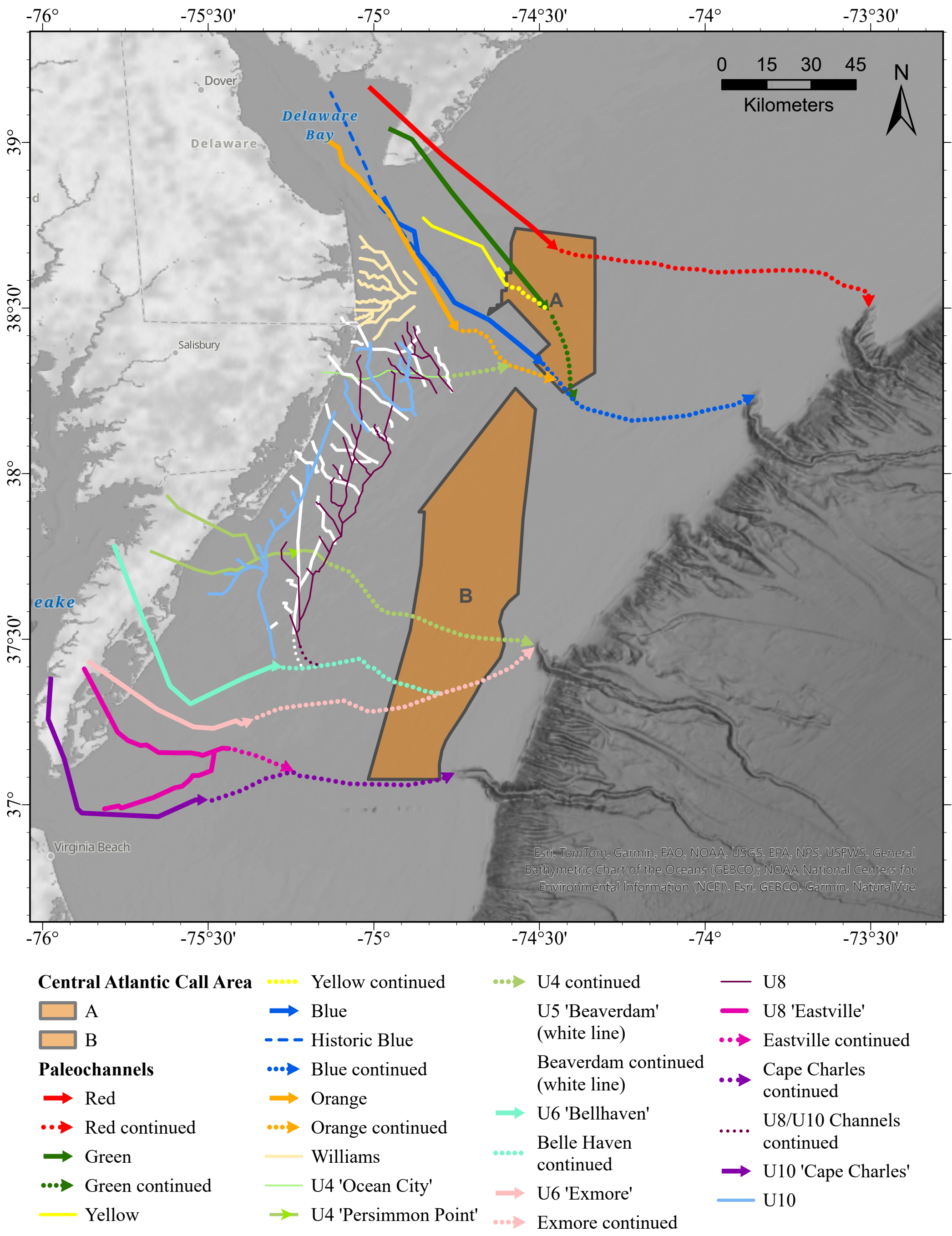


Figure A1. Map of the Central Atlantic Call Areas A and B within the Mid Atlantic Bight continental shelf that illustrates the bathymetric depth contours at 30, 60, and 900 meters(BOEM, 2022).

Appendix A: Figures



Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS, General Bathymetric Chart of the Oceans (GEBCO); NOAA National Centers for Environmental Information (NCEI). Esri, GEBCO, Garmin, NaturalVue

Figure A2. Map showing the paleochannels running through Call Area A, including the Red, Green, Blue, Yellow, Orange, Williams, and Rio Grande channels. Also highlights paleochannels that run through Call Area B, including the Persimmon Point, Ocean City, Beaverdam, Exmore, Belle Haven, Eastville, and Cape Charles channels. Modified from Brothers et al. (2020) and Childers (2014) figures.

Table A1. Table showing abbreviations and names of formations from different formation studies conducted for the Delaware Geologic Survey (DGS), New Jersey (NJ), and the Delmarva Peninsula (DMP). The sediment and units contained in each formation is listed as well as the depth of those formations. The location and age of the formation is listed if mentioned in the above studies (Brothers et al., 2020; Woods Hole, 2021; Lofi et al., 2013; USGS, 2013).

Abbreviation	Name	Study	Sediment Present	Contains Units	Depth/ depth within formation	Era	Specific Location if mentioned
Tbd(T stands for Tertiary	Beaverdam Formation	DGS, NJ (Qbd in DMP)	unconsolidated medium-grained quartz (silica) sand, with some coarse and fine sand mixed in	pebbles(4–64 mm), granules(2-4 mm), and a minor amount of white silt.		Pliolocene	
			coarser sand		upper	mid-to-late-Wisconsonian/late Pliestocene	
Qsi (Q stands for Quaternary)	Sinepuxent Formation	DGS	fine-grained sand with thin beds of clay		lower	mid-to-late-Wisconsonian/ mid to late Pliestocene	
Qo	Omar Formation	DGS	alternating silts and sands above thicker sand		-	mid pliestocene	
			primarily sand		upper 25 m	-	
Qms	marine shelf deposits	DGS	very fine sand, silt, clay		beneath 25 m	-	
Ql	lagoonal deposits	DGS, NJ	majority mud -some sand associated with paleovalleys			-	
			fine, well-sorted sand. Burrowed interbedded clayey silts and silty sands		upper		
Qlh	Lynch Heights Formation	DGS, NJ	heterogeneous medium to fine siliceous sand with discontinuous beds of coarse sand, gravel, silt, fine to very fine sand, and organic-rich clayey silt to silty sand	fluvial to estuarine unit of fluvial channel, tidal flat, tidal channel, beach, and bay deposits	15m	Mid pliestocene	parallel to DE Bay
Qrl	ravinement lag deposits	DGS	fine- to medium-grained silty sand	traces of clay associated with the flooding of the Beaverdam and Omar formations	-	Pleistocene	
Qfs	finger shoal deposits	DGS				-	
Qns	nearshore deposits	DGS				-	Right along coastline
Qss	sansheet deposits	DGS, NJ				-	
Qqw	quiet water deposits	NJ				-	
Qm	marsh deposits	NJ				-	
Qsl	shoal deposits	NJ				-	
Qmn	(HST) marine deposits: sand, ridges, modern deposits	DMP	sand			Modern/Holocene	
U11	(TRS) seafloor in many places	DMP			8–35 m below MLLW	Present to MIS2(.01 Ma)	
Qcch	(TST) hilly surface filling in Cape Charles Paleochannel	DMP		TRS present within and tidal/ back barrier deposits above		Holocene/LGM to MIS2 (.01Ma)	
U10	Base of Cape Charles Paleochannel	DMP		closer to shore it is mixed with TRS; relief on the order of 3–8 m	3–6 m below MLLW	.018Ma	South study area
U10	Base of tributaries flowing into Cape Charles Paleochanel	DMP		relief greater than 23 m		.018Ma	North(Assatague) [ancestral Susquehanna River]
Q2	HST estuarine and marine sediments- not paleochannel fill genetically related to U11(Seafloor)	DMP				Quaternary	
U9	TRS merges with U7	DMP			14–43 m below MLLW	Pleistocene	
Qe	TST filling Eastville paleochannel, tributaries, and drainage networks genetically related to Q2	DMP				MIS 6(.12-.15Ma)	
U8	Base of Eastville paleochannel	DMP		greater than 20 m of relief in shore-parallel seismic profiles	between 20 and 80 m below MLLW		ancestral Susquehanna River and tributary to ancestral York and/or James rivers
Q1	HST shelf and estuarine sediments- not paleochannel fill above U7	DMP				Pleistocene	not in south of study area
U7	TRS merges with U9	DMP			18–52 m below MLLW	Pleistocene	
Qx	TST that contains sediment from Q1 that is a fill of the Exmore and Belle Haven Paleochannels	DMP				Plesistocene MIS 8-MIS 12 (.2-.4)	
U6	Base of Exmore paleochannel and Belle Haven paleochannel	DMP		relief of 15m max	28 and 74 m below MLLW	Plesistocene MIS 8-MIS 12 (.2-.4)	Exmore: ancestral susqueanna Belle Haven: ancestral tributary ffor susqueanna(likely rappahanock rover)
Qbd	LST fill for the beaverdam braided fluvial and deltaic plains, below U7 and has similar fill to Qx that is slightly younger	DMP	amalgamated sediments(high energy systems), and same as Tbd above		maximum of 29 m	Older than Qx	
U5	base of Beaverdam paleochannel	DMP			25 and 80 m below MLLW	Pleistocene	
Qpp	TST Persimmon Point and Ocean City paleochannel deposits	DMP				Plesistocene	
U4	Base of Persimmons Point and Ocean City paleochannels	DMP		up to 15 m of relief in shore-parallel profiles	18 to 76 m below MLLW with the unconformity exhibiting	Plesistocene	formed by the Susquehanna, Potomac and possibly other, rivers
T2	HST Coastal Plain marine sediments base of many Quartnary paleochannels and U7 and U9 are the upper bounds (seafloor during that time period)	DMP		less than 10 m of relief		Pliocene	
U3	TRS	DMP			24–95 m below MLLW	Pliocene	
Tchy	TST paleochannel infill- U3 is above it moveing shoreward it is truncated by quaternary processes	DMP				pliocene	
U2	base of Tchy paleochannels	DMP				Pliocene (older than Tchy0	
Tchb	TST paleochannel infill	DMP				pliocene	
U1	Base of Tchb paleochannels	DMP			38 to 112-m below MLLW	pliocene	
T1	HST (seafloor during that time period)	DMP			within 30 m of the seafloor and further	Later Neogene	

Tables

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Table A2. Table showing the hazard, description impact and risk along with an associated mitigation strategy.

Hazard	**Description**	**Impact on Turbine Stability/ Placement**	**Risk Level (Low, Medium, High)**	**Mitigation Strategy**
Sediment Variability	Differences in sediment composition and layer consistency	High	High	Site-specific foundation design, additional sediment testing
Paleochannels	Ancient riverbeds filled with fine sediment prone to movement	High	High	Avoidance, geotechnical analysis, appropriate foundation type
Glauconite Sands	Thixotropic sediments that reduce pile capacity	Medium	Medium	Pre-drilling, drill-drive-drill technique, suction caisson foundation
Storm Surge	Coastal storm impact causing sediment displacement and scouring	High	Medium	Scour protection, deeper foundations, erosion barriers
Earthquake Activity	Potential for soil liquefaction and sediment displacement	High	Low	Site selection analysis, earthquake-resistant foundations
Unexploded Ordnances (UXOs)	Potential hazards from buried military ordnances	High	High	Site surveying, avoidance, UXO removal
Shipwrecks/Obstacles	Obstructions from shipwrecks or artificial reefs	Medium	Medium	Site surveying, avoidance, clearance if feasible
Submarine Canyons	Areas of steep underwater slopes prone to sediment slumping	Medium	Medium	Avoidance, selection of alternative foundation types
Human-Made Structures	Existing infrastructure (e.g., pipelines, cables)	High	Medium	Mapping of structures, avoidance, regulatory coordination

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Competing interests. This research may involve competing interests across several areas. First, offshore wind developers and their associated stockholders may benefit financially from the findings and recommendations provided here. Additionally, BOEM and the Delaware Geological Survey (DGS) is undertaking a geologic survey of the Mid-Atlantic Bight, though the specific scale of this project is not publicly available. Personal and professional relationships may also introduce potential biases, as some of the sources referenced in this research are authored by individuals who are affiliated with or have attended the University of Delaware, where I am also affiliated. Furthermore, intellectual biases may affect my interpretations, particularly in my approach to paleochannel directions, which is informed by my experience with bathymetric contours and maritime mapping. Lastly, institutional affiliations could influence this work, as the University of Delaware, along with many offshore wind developers—especially those with projects south of New Jersey—stand to benefit from the research findings.

Disclaimer. The findings and opinions expressed in this paper are those of the authors and do not necessarily reflect the views of the University of Delaware, the Graduate College, or any affiliated organizations. This research is intended for academic and informational purposes only. While every effort has been made to ensure the accuracy of the data presented, the authors acknowledge that subsurface data is limited, preventing a full scope of subsurface natural hazards from being assessed. This research is also specifically focused on the sediments within the Mid-Atlantic Bight and is not representative of all hazards that may be present in offshore wind projects. Additionally, the authors recognize the potential for further research to enhance understanding of the subject. The authors are not liable for any decisions or actions taken based on the information provided herein. Any conflicts of interest have been disclosed in the relevant sections of the paper. This paper has benefited from the use of AI for writing assistance in refining parts of this paper, ensuring clarity and coherence, which contributed to editing and formatting but not to data interpretation or analysis.

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