SUITABILITY MODELS FOR FLOATING OFFSHORE WIND FARMS ALONG THE U.S. MID-ATLANTIC MARGIN

by

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of the requirements for the degree of Master of Science with a major in Geology

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LIST OF ABBREVIATIONS

AOI – Area of Interest

BOEM – Bureau of Ocean Energy Management

BPI – Benthic Position Index

DEM – digital elevation model

FOWF – floating offshore wind farm

FOWT – floating offshore wind turbine

km – kilometers

m – meters

NCEI – National Centers for Environmental Information

NOAA – National Oceanic and Atmospheric Administration

PGA – peak ground acceleration

TLP – tension-leg platform

U.S. – United States

USGS – United States Geological Survey

WEA – Wind Energy Area

ABSTRACT

The Bureau of Ocean Energy Management, in support of the United States' (U.S.) national energy goals, designated eight draft wind energy areas (WEAs) along the Mid-Atlantic continental margin of the U.S. Draft WEAs E-1, E-2, and F are all deepwater sites (>1,500 meters), requiring the use of floating offshore wind technologies. This thesis investigates the suitability of deploying floating wind technologies in draft WEAs E-1, E-2, and F, focusing on the potential impacts of geohazards in the region. Geological data of the slope gradient, seafloor complexity, and sediment type were analyzed via ArcGIS Pro to produce five weighted overlay suitability analysis models. The results suggest that all three draft WEAs are suitable locations for the deployment of floating offshore wind turbines. WEA E-1 is the most complex and contains the highest slope gradients (up to 35°), but shows minimal risk in the southern half of the area. WEA E-2 is the opposite and has a much more suitable northern half, due to the massive Washington Canyon that extends out to the WEA's southwestern border. WEA F, though a very small area, is an optimal location with no submarine canyons in close proximity and the lowest slope gradients among the WEAs. These findings, though indicative of feasible locations for floating turbines, are meant to shed light on the potential risks of developing on the Mid-Atlantic continental slope and rise. Further geological surveying is needed in the region prior to any development, as seabed features change over time and the likelihood of slope failure varies.

Chapter 1

INTRODUCTION

In 2022, about 60% of electricity generation in the U.S. was from fossil fuels, while only 22% was from renewable energy sources and 18% from nuclear energy.[1] The U.S., after it rejoined the Paris Agreement, stated that in order to limit the global temperature increase to 1.5°C, net zero emissions will need to be reached by 2050.[2,3] To do so, the Biden-Harris Administration set a national target in March 2021 for the U.S. to deploy 30 gigawatts of renewable offshore wind energy by 2030.[3,4] According to the *Offshore Wind Market Report: 2023 Edition*, the U.S. currently has 42 megawatts in operation and 932 megawatts to be operational by 2024.[4] Rapid growth of the U.S. offshore wind industry is required to meet the national target.

On behalf of the Biden-Harris Administration, the Bureau of Ocean Energy Management (BOEM) defined eight draft wind energy areas (WEAs) along the Mid-Atlantic continental shelf, slope, and rise.[5] Three of these draft WEAs are deepwater sites (>1,500 meters (m)) that require floating offshore wind technologies. These sites, draft WEAs E-1, E-2, and F are the primary focus of the research in this thesis. Located in part on both the continental slope and rise, depths range from 1,550 m to 2,640 m for E-1 and E-2 and 2,375 m to 2,390 m for F (Figure 1). WEAs E-1 and E-2 cover larger areas and are situated farther from shore than WEA F. Area E-1 is approximately 190,405 hectares and 132.2 kilometers (km) from shore. Area E-2 encompasses nearly 139,163 hectares and is 137.8 km from shore. Area F is slightly closer to shore, situated 123.2 km, and comprises a much smaller area of approximately 17,003 hectares.[5] If spaced one nautical mile apart, around 60 turbines could be deployed in WEA F. That is potentially enough for a 500 MW wind farm, depending on the turbines' nameplate capacity.

This thesis has three main objectives: (1) to examine the suitability of floating foundations within draft WEAs E-1, E-2, and F; (2) to investigate the role of geohazards such as earthquakes and submarine landslides in the region, along with the probability of slope failure; and (3) to develop suitability models for floating turbines in WEAs E-1, E-2 and F based on slope gradient, seafloor complexity, and sediment type.

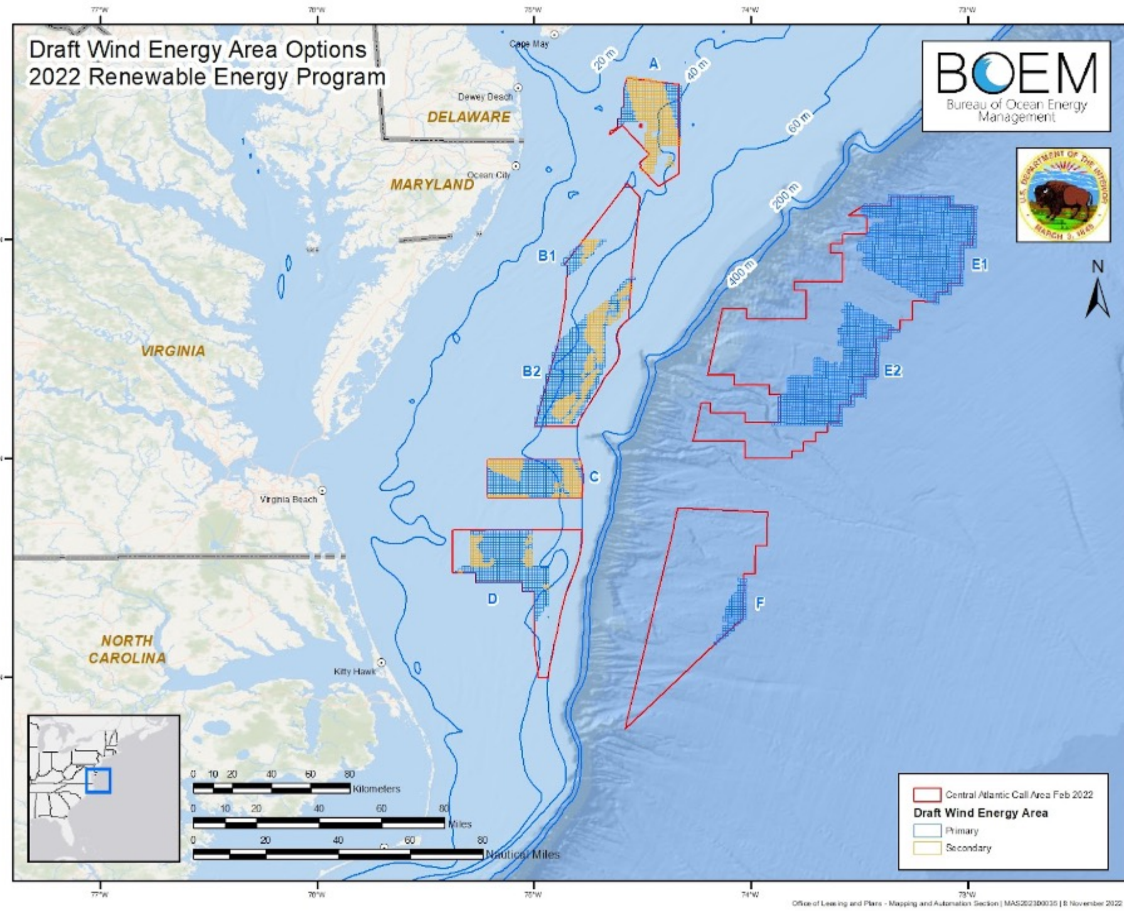

Figure 1: Map of the draft WEAs for the Central Atlantic, with focus areas E-1, E-2, and F depicted furthest east from the coast off the continental shelf.[2]

Chapter 2

BACKGROUND

2.1 Floating Offshore Wind Energy

Currently, fixed-bottom foundations for offshore wind turbines are limited to installation in waters up to approximately 50 m. Given that in general winds are stronger with increasing distance from shore, "floating foundations could be game changers," as they eliminate fixed-bottom depth constraints allowing access to deeper waters further offshore.[6] Depths in WEAs E-1, E-2, and F are well beyond the 50 m mark, requiring the utilization of floating foundations in the development of any offshore wind projects in these WEAs.[6]

Unlike fixed-bottom foundations, floating foundations are attached to mooring cables that are anchored to the seabed.[7] Each of these elements, the foundation, cables, and anchors, have important roles that allow for the proper functioning of floating turbines. These will be discussed in subsequent sections.

2.1.1 Foundation Types

Many of the foundation designs for floating offshore wind turbines (FOWTs) are modified from concepts utilized by the offshore oil and gas industry. There are five basic types of floating foundations: spar, semi-submersible, barge, tension-leg platform (TLP), and multi-turbine platform. Of these five types, spar, semi-submersible, and TLP are the designs most commonly considered in projects under development.[8]

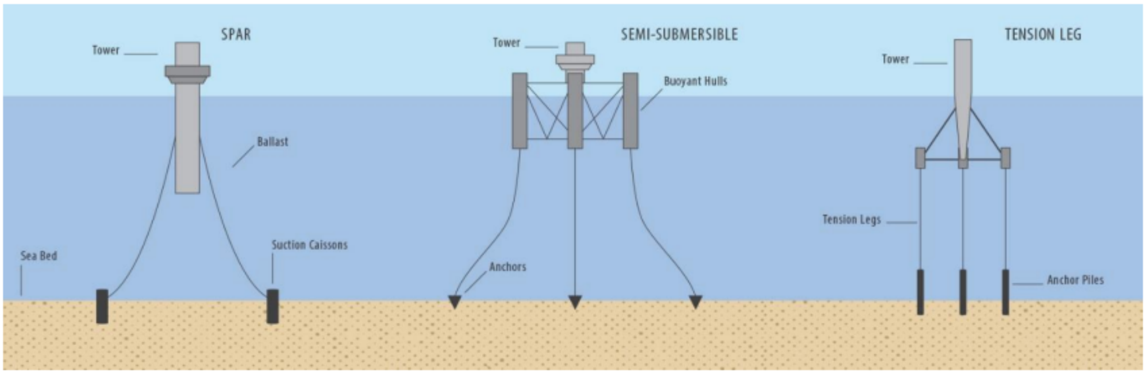

Figure 2: Main types of FOWT foundations.[8]

Spar, or spar buoy foundations consist of a single cylinder with a ballasted substructure that holds the turbines upright.[8] This foundation, shown on the left in Figure 2, is noted for its simplicity, but can only be used in waters deeper than 100 m.[6] Currently, there are only a few offshore wind farms utilizing spar foundations. The Hywind project floating turbines use the single ballasted cylinder concept and mooring cables. Another example is the Fukushima FORWARD project Advanced Spar (Fukushima Hamakaze) that is designed with upper and lower hexagon-shaped hulls that are attached by a single cylinder. Lastly, there is the SeaTwirl project design, which includes a floating turbine and a keel that is used to maintain the stability of the structure.[7]

The semi-submersible floating foundation design shown in the middle of Figure 2 has multiple submerged columns, or hulls, that are connected to each other with braces that work to keep the structure afloat.[8] Along with the hulls, mooring lines and anchors are used to help resist overturning. Unlike the spar design, semi-submersible foundations can be constructed onshore and can be deployed in shallower depths (<100 m). However, in comparison to the spar buoy, the semi-submersible requires more materials for construction and the installation is more complex.[6] Globally, there are currently four projects with semi-submersible foundations installed and many more under development. Three of those four are the VolturnUS, Fukushima FORWARD compact, and Fukushima FORWARD V-shape. They all utilize a similar design where three side columns are linked together, and the turbine is mounted on a center column. The fourth concept that has been installed is the Windfloat, which also uses three columns with the turbine situated on one of the three columns.[7]

The tension-leg platform, shown on the right in Figure 2, consists of a highly buoyant central column with tendons moored to the seafloor. Utilizing tension forces, the tendons stabilize the structure and minimize its movement.[8] There are currently no operating offshore wind farms using this foundation type.[6]

2.1.2 Mooring Systems

Mooring systems are the components of FOWTs that maintain the position of the floating turbines. Each mooring system needs to be adapted to fit the type of foundation and the site conditions. For example, spar foundations require longer mooring lines with extra weight to compensate for the vast movements they make. If a project were to utilize a TLP instead of a spar design, the mooring lines would be much shorter. This is due to TLPs relying on restraint and limited foundation movement. Long mooring lines would not be able to be as tightly secured as shorter ones. A similarity among the different FOWTs is the number of moorings needed.

They all require a minimum of three mooring lines to stay upright and function properly.[9]

Different types of mooring systems are plain catenary, multi-catenary, buoyant semi-taut, or taut. Plain catenary moorings (Figure 3, top left) consist solely of weighted ground chains attached from the foundation to the anchors.[9] Due to its simplicity, this design is currently the most common type used in the industry.[10] Multi-catenary systems (Figure 3, bottom left) incorporate synthetic ropes in addition to the chains used in plain catenary. Buoyant semi-taut moorings (Figure 3, top right) also use synthetic rope and chain combinations and add a few buoyancy elements on the ropes to prevent wearing on the seabed. Taut systems (Figure 3, bottom right) are comprised of rope tendons secured tightly to the anchors in order to establish great enough tension to keep the foundation in place.[9]

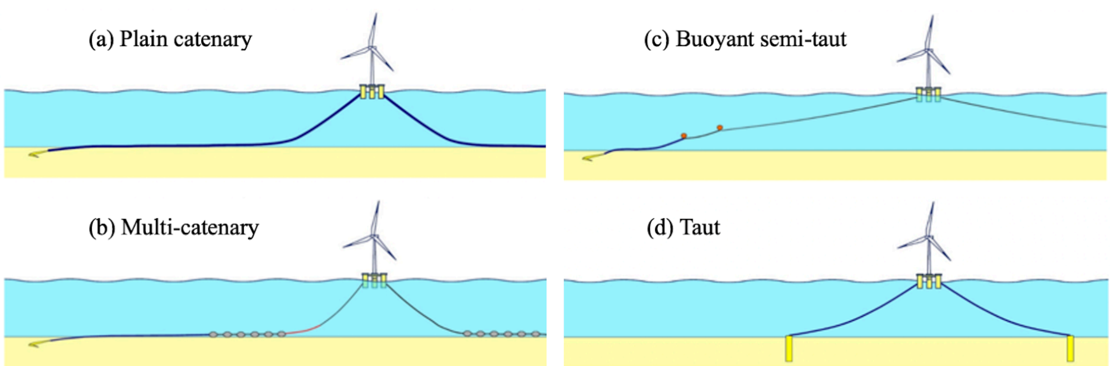

Figure 3: Mooring systems used for FOWTs: (a) plain catenary, (b) multi-catenary, (c) buoyant semi-taut, (d) taut (modified from Timmington, 1982)

2.1.3 Anchorage Systems

When it comes to the design of FOWTs, determining the best way to anchor foundations to the seabed is of utmost importance. Like mooring systems, anchoring is dependent on the site conditions. Sediment type is the driving factor in deciding which anchor types will be used to maintain turbines in their positions.[10] The layering in soil profiles can result in varying levels of efficiency for anchors at each point of installation. Because of this, it is good practice to combat any uncertainties in soil type by adding more weight to the anchors and increasing the spacing between them.[11] It is also important to ensure that the anchoring systems being used are reliable and support the optimization of the turbines' performance. As of now, anchoring systems can be placed into one of three groups: (1) gravity-type, (2) pile-type, or (3) plate-type.[10]

Gravity-type anchors, though quickly operational upon installation, offer the lowest efficiency among the three types. Making use of the force of gravity to function, these anchors are heavy weights that are situated on the seafloor with little to no ground penetration. They resist movement well and only mobilize a minor volume of near-surface sediments, however, failure may occur if the anchor's bearing capacity is reached by horizontal stress from the mooring lines.[10] Pile-type anchors are cylindrical tubes embedded into the seafloor. Driven piles, the most common anchor used for offshore wind turbines, are hammered into the seabed until the top of the tube is roughly at ground level. Another pile-type anchor, suction piles, pump water through the tube to create a pressure difference that sucks the pile down and holds it in place. These can be difficult to install in hard, consolidated clays and heterogeneous soil profiles due to the resistance properties of clays. Finally, plate-type anchors have the highest-ranking efficiencies. The entirety of plate-type anchors are installed within the seabed and resist movement by mobilizing large volumes of soil. Of this type, drag embedment anchors are well-known and trusted. They work by being dropped on the seafloor, and then dragged until they cut into the seabed and reach their penetration depth.[10]

2.2 Overview of the Mid-Atlantic Margin

The morphology of the Mid-Atlantic margin of the U.S. is a passive margin that formed over 200 million years ago as a result of North America and Africa rifting apart.[12,13] The extent of the margin is from Georges Bank in the north to the Straits of Florida in the south and consists of four major basins created by rifting processes. Those basins are the Georges Bank Basin, the Baltimore Canyon Trough, the Carolina Trough, and the Blake Plateau Basin.[13] Of the four basins, this thesis solely considers the Baltimore Canyon Trough, as it is the only one within close proximity to the WEAs.

The Atlantic margin comprises three main regions: the continental shelf, slope, and rise. The continental shelf begins along the coast and extends eastward to the shelf break.[12] The transition from the shelf to the slope is made apparent by the abrupt change in depth. Due to its complexity and wide range of depths, the continental slope can be broken up into an "upper" and a "lower" section. Many publications separate the sections between 1800 and 2000 m where there is a major change in seafloor gradient. They also tend to refer to the lower slope as the "upper rise" based on the morphology. Regions with evidence of sediment transport are typically labeled as lower slope, whereas regions dominated by deposition are on the rise. The transition onto the continental rise generally occurs between 4000 and 4500 m.[13]

Another important aspect, besides the varying depths of the Atlantic margin, is the seafloor gradient. The shelf break marks where gradients greatly increase on the slope, but eventually transitions back to gentle gradients on the rise. The slope has the steepest gradients of the entire margin, with the majority of the region ranging from 4–8°. However, gradients reach 8–12° in certain areas between the Hudson Canyon and Cape Hatteras, which covers where the WEAs of interest are located.[14] These steep seafloor gradients have a huge influence on the sediment transport processes of the slope. The dominant morphological feature of the slope, submarine canyons, plays a major role in sediment transport from the shelf out onto the rise.[12] Submarine canyons in the Mid-Atlantic region, due to their potential negative impact on FOWTs, are discussed in depth below.

2.3 Potential Geohazards

2.3.1 Submarine Canyons

Several studies have shown that submarine canyons are the prevailing geomorphic feature of the U.S. Mid-Atlantic continental slope.[12,15,16] A total of 51 submarine canyons, many of which are located in the Mid-Atlantic region, have been identified on the continental slope of the eastern U.S. from a series of sidescan-sonar surveys conducted in 1979.[16] In fact, some even appear to border the WEAs, such as the Wilmington and Washington Canyons (Figure 4), making them notable characteristics to include in this study.

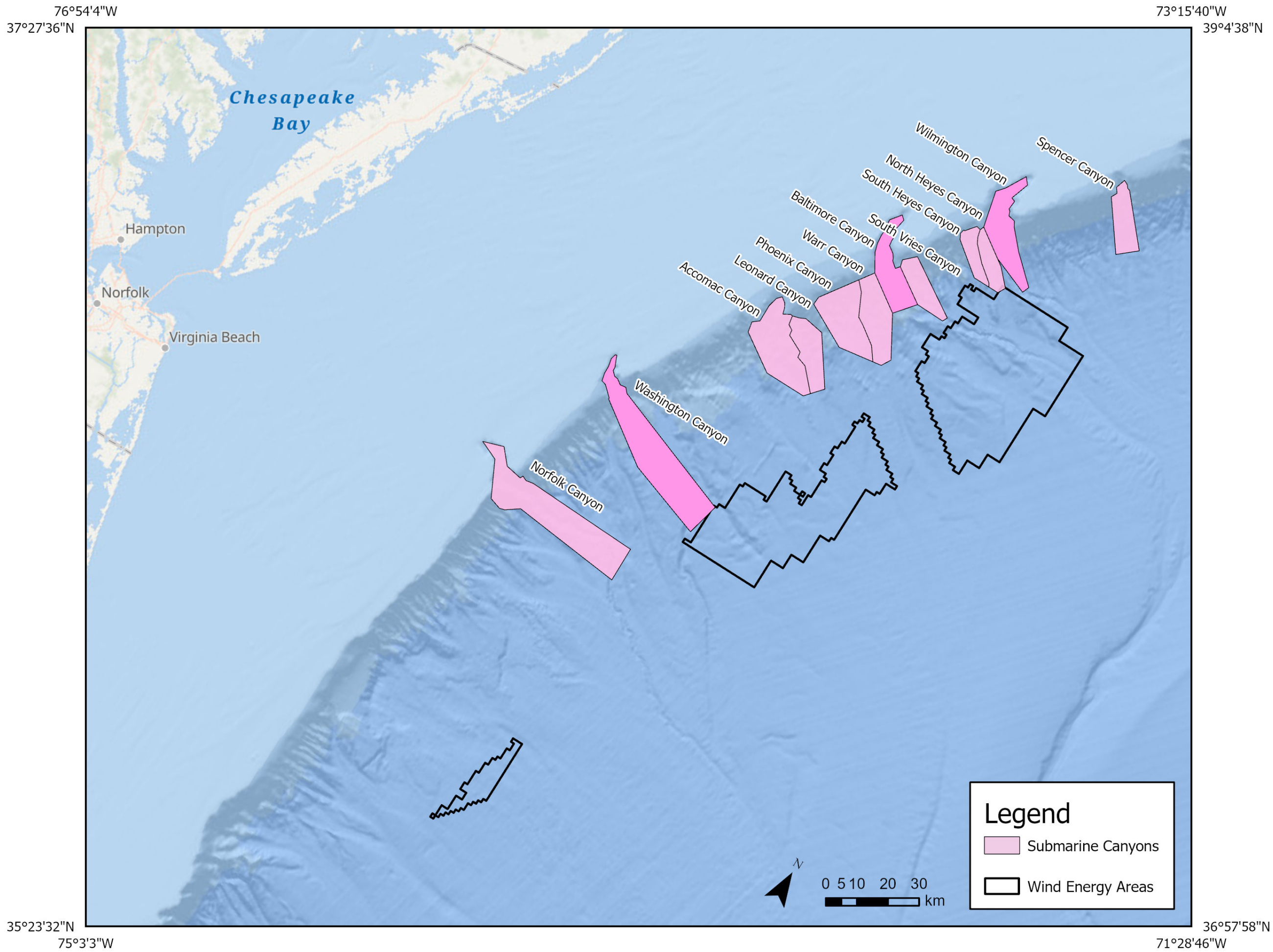

Figure 4: Locations of submarine canyons with respect to the draft WEAs. Darker shading is applied to canyons referenced in text.

Submarine canyons are defined as valleys having "V-shaped profiles, high steep walls with rock outcrops, a winding course, and numerous tributaries entering from both sides."[16] They can appear in various forms, ranging from practically straight to highly sinuous. Due to the age of indentations left by canyons along the continental shelf, it is thought that they originate on the slope and erode up to the shelf over time.[16] Gravity and sediment influence this erosion process, as sediment tends to be directed down the slope where they are deposited. In this process, sediments bypass deposition on the shelf, and instead erode materials that then flow down the slope.[12]

Although most submarine canyons follow a trend of merging toward the middle and lower continental slope, the Baltimore and Wilmington Canyons do the opposite. They can be seen on sonar imagery with channels that diverge eastward away from the direction of the slope.[16] The morphology and trend direction of the Baltimore Canyon has induced deposition on the southern slope where the channel diverges. This buildup of sediments, which were likely transported by mass wasting and by turbidity currents, has led to slope instability and failure along parts of the canyon.[15] The Wilmington Canyon also contributes to sediment transport on the slope. Seismic-reflection profiles generated by the U.S. Geological Survey (USGS) in 1977 and 1978 contained evidence of valleys within the canyon that erode and move sediments. These erosional processes are still active in the canyon today, transporting sediments down the slope and depositing them onto the continental rise.[17]

Though the presence of nearly all the submarine canyons in the Mid-Atlantic region are relevant to offshore development, perhaps the most compelling evidence of slope instability sits just north of the Washington Canyon. Examinations of the seafloor bathymetry and the stratigraphy of the area shows that it has characteristics very similar to that of the Currituck Slide Complex. The slide complex, offshore of Virginia, has an upper slope with minimal canyon evolution. However, the mid-to-lower slope contains a large volume of deposited sediments. Conditions like these are ultimately what caused the Currituck Slide failure that displaced a massive volume of sediments over an area greater than 6500 km^2.[18]

2.3.2 Submarine Landslides

The occurrence of submarine landslides within the U.S. Atlantic margin is relatively common. There have been 160 landslide scars surveyed along the Mid-Atlantic slope and rise with depths of origin ranging from 1000 to 2000 m.[13] Depending on their origin, or source area, submarine landslides can be divided into two categories: canyon sourced and open-slope sourced. Canyon sourced landslides tend to originate at shallower depths less than 1000 m on the middle and upper continental slope. They have gentler gradients and overall have been found to cover smaller areas with less volume. Conversely, the majority of open-slope sourced landslides originate at deeper depths between approximately 1500 - 2500 m. Having steeper gradients, these landslides begin on the upper rise and the lower slope, and they cover much larger areas with higher sediment volumes.[12,14] Of the surveyed landslides in the Mid-Atlantic region, open-slope landslides appeared to be more prevalent than those originating in canyons.[19]

Aside from where submarine landslides are sourced, there are many factors contributing to slope instability that pre-condition areas for failure. Studies of historic landslides have shown that accumulations of thick sedimentary deposits are commonly associated with slope failures.[13,18] Specifically, most failures can be linked to finer-grained, unconsolidated sediments with low-permeabilities and high pore pressures. When sedimentary deposits of this nature accumulate on the slope or upper rise, the layer is likely to be unstable and subject to failure at any time.[12]

In addition to the nature of the sediments, areas with high seafloor gradients increase the likelihood of slope failure. The deposition of thick sediment layers on steeper portions of the slope is potentially a recipe for disaster.[12,13] The Currituck Slide Complex fit these conditions, and ended up resulting in a widespread failure. Indeed, the Currituck Slide did have another component of slope failure, decreased shear strength.[18] Reducing the shear strength of materials pre-conditioned for failure is often the final piece needed for the failure to occur, and this is primarily brought on by trigger mechanisms like earthquakes.[14]

2.3.3 Seismicity

Though earthquakes do not occur as frequently off the U.S. East Coast as they do the West Coast, they are still the leading cause of submarine landslides and slope failures. Analyses have attributed earthquakes to translational failures that have occurred along the continental margin.[13] Looking into historic earthquakes in the Mid-Atlantic, there have been 13 earthquakes recorded in the past 50 years that had epicenters within a 300 km radius of a WEA. The largest of these seismic events had a magnitude of 4.8, while the closest one to the WEAs had a magnitude of 4.6. This particular earthquake occurred in January of 2019, and its epicenter was a mere 39.21 km away from the easternmost side of WEA E-1. Since 2020, there have not been any recorded earthquakes within the 300 km radius.[20]

Regardless of magnitude or location, there were not any submarine landslides or slope failures of that resulted from those seismic events. Nevertheless, one study has noted areas on the outer continental shelf in the Mid-Atlantic that are potentially in the initial stages of slope failure. Off the coast of southern Virginia and North Carolina, between the Norfolk Canyon and Currituck Slide Complex, a system of echelon cracks was discovered. Upon assessing the features in vertical cross section, the scientists conducting the study theorized that the asymmetric shape of the cracks are representative of a slip that had occurred on the surface.[21] Further investigation into these features should be undertaken prior to the development of floating offshore wind farms (FOWFs) in this region, as the location could potentially impact WEA F.

Chapter 3

METHODOLOGY

The study conducted in the report *Potential Earthquake, Landslide, Tsunami and Geo-Hazards for the U.S. Offshore Pacific Wind Farms* by RPS Group was used as a framework for the methods utilized in this thesis.[22]

3.1 Data Collection

3.1.1 Bathymetry

Bathymetric data were retrieved from the National Oceanic and Atmospheric Administration (NOAA) Bathymetric Data Viewer.[23] A digital elevation model (DEM) was extracted from the National Centers for Environmental Information (NCEI) DEM Global Mosaic with cell sizes of 3 arcseconds, which is approximately 90 m x 90 m per cell. The grid covered an area within 38.5°-35.5° N, 72°-76° W, encompassing the WEAs and extending well beyond them to include the depths where the continental shelf transitions to the slope.

3.1.2 Seafloor Complexity

The data on seafloor complexity of the Mid-Atlantic region were obtained from Dr. Marta Ribera at The Nature Conservancy. The complexity is meant to act as a measure of how diverse the seafloor is in a given location. In their work, Dr. Ribera with others utilized bathymetric data from NOAA's Bathymetric Data Viewer to calculate the Benthic Position Index (BPI). The standard deviation of the BPI for each cell was then calculated with the idea that this would capture the “bumpiness” of the terrain. In the end, the goal was to have a data layer representing fine-scale features, such as peaks and valleys. Areas with a higher count of these features are considered to have a high complexity, whereas areas with fewer valleys or peaks are marked as having low complexity.

This data layer, however, has several limitations. Because the layer is based on bathymetry, it is only as good as the bathymetry used for the calculations. Ocean bathymetry is not static, and thus, complexity is subject to change over time as features evolve on the seafloor. It should also be noted that the most recent update of the bathymetric data was September 2020. Another consideration is that the method used by Dr. Ribera to determine the complexity is one of many. Currently, there is not an agreed measure of complexity. According to Dr. Ribera, NOAA has also used a measure of rugosity to show sea surface roughness, as well as the “percent slope” or “slope of slope” values for complexity due to the potential relationship with the presence of coral habitats. Though all these methods are derived from ocean bathymetry, Dr. Ribera’s dataset was chosen for this thesis because it covers the entire area of interest (AOI), and it paired well with the other layers. The use of the complexity data with the other layers is discussed further in Section 3.4.1.

3.1.3 Sediments

For the sediment types, data were collected with a focus on the sediments within and nearby the WEAs. Using the bounding coordinates of 38.5°-35.6° N, 72.8°-74.75° W, data were extracted from the USGS usSEABED dataset.[24] The extracted dataset included information on where and at what depth samples were taken, as well as the weight percent and Folk classification of sediment types. The amount of gravel, sand, mud, and clay in each sample was given a weight percent between 0 and 100. The Folk classification was then assigned to each sample based on the weight percent values.[25]

3.2 Data Processing

Prior to conducting the ArcGIS Pro suitability analysis, bathymetry, seafloor complexity, and sediment type data were processed and mapped into a raster format. This was a requirement for running the ArcGIS Pro Weighted Overlay tool. A buffer of 8 km was created around the WEAs using the Buffer Analyst tool. Extending the study area around the WEAs by 8 km allowed for adequate data coverage both within the WEAs and in the general vicinity of the overall AOI.

3.2.1 Slope Gradient

The .geoTIFF NCEI DEM Global Mosaic image from NOAA, already in a raster format, was imported to ArcGIS Pro. Using the Slope Spatial Analyst tool, the slope gradient was calculated from the bathymetry values in the dataset. These values, originally formatted as floating points, were then converted into integers with the Int Spatial Analyst tool. Based on the distribution of values, the data were divided into three groups: 0°-5°, 5°-10°, and greater than 10°. The final processing step was using the Extract by Mask tool to create a layer showing data only within the WEAs and the 8 km buffer zone.

3.2.2 Seafloor Complexity

The seafloor complexity data were obtained as a .tif image, so the data processing followed similar steps to those for the slope gradient. Once the data were imported to ArcGIS Pro, only the Int tool was needed to convert the values into the required format. Then, the 8 km buffer was generated using the Extract by Mask tool. The original dataset included seafloor complexity values of 0 to 3, in which the complexity was ranked as either low, medium, high, or very high. These four classifications are represented on the raster map, however, they had to be adjusted for running the suitability analysis. These adjustments are discussed in Section 3.4.3.

3.2.3 Sediment Type

The extracted USGS usSEABED dataset was imported to ArcGIS Pro as a .csv file, from which the data were plotted. Since the dataset was organized by geographic coordinates, the Feature to Polygon Data Management tool was used to convert points of similar values to polygons. It should be noted that this tool made assumptions about the sediment type in areas where samples were not obtained. Further geological investigation that includes collecting additional sediment samples should be completed prior to offshore wind project development in this AOI.

Five classifications were established from the available samples for the sediment types in the AOI: gravelly sand, sand, muddy sand, sandy mud (clay), and mud (clay). These grain-size classifications were based on the triangular diagrams derived by Folk et al.[25] Two textural classification diagrams were used, one for gravel-free sediments and one for gravel-bearing sediments. The gravel-free samples were defined by the percentage of sand and the ratio of silt to clay. Likewise, the gravel-bearing sediments were defined by the percentage of gravel and the ratio of sand to mud. Samples containing 5-30% gravel and a 1:9 ratio of mud to sand were recorded as gravelly sands. This was the only gravel-bearing sediment type for the AOI, making the remaining four types gravel-free. Any samples greater than 90% sand were marked as sand. The notation of muddy sand was given to samples consisting of 50-90% sand

and a 1:1 ratio of clay to silt. Sandy mud (clay) was used for samples with 10-50% sand and a 1:1 ratio of clay to silt. The last sediment type identified was mud (clay), which was given for less than 10% sand and a 1:1 ratio of clay to silt.[25]

After classifications were applied to the polygon layer, the Feature to Raster Conversion tool was used to turn the layer into a raster format. Then, mirroring the slope gradient layer, the Extract by Mask tool created an 8 km buffer of the sediment types, and the Int tool converted the values to integers.

3.3 Integer Raster Maps

Upon completion of processing the datasets, three integer raster maps were produced. The three maps are representative of the slope gradient, the seafloor complexity, and the sediment type for the draft WEAs and the surrounding region. These display the processed integer data as is, prior to the reclassification performed for the weighted overlay models.

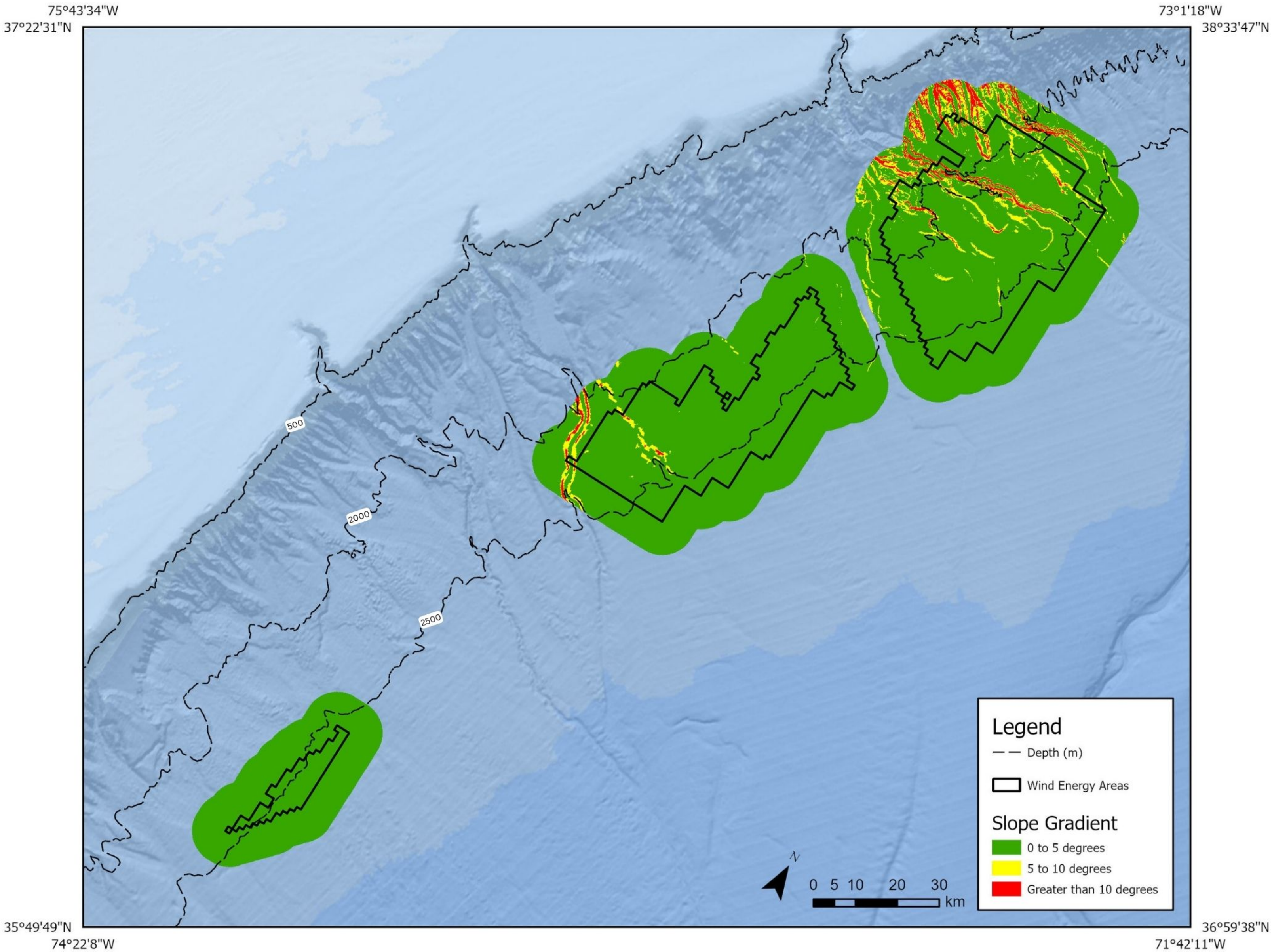

Figure 5: Raster Map 1 – slope gradient

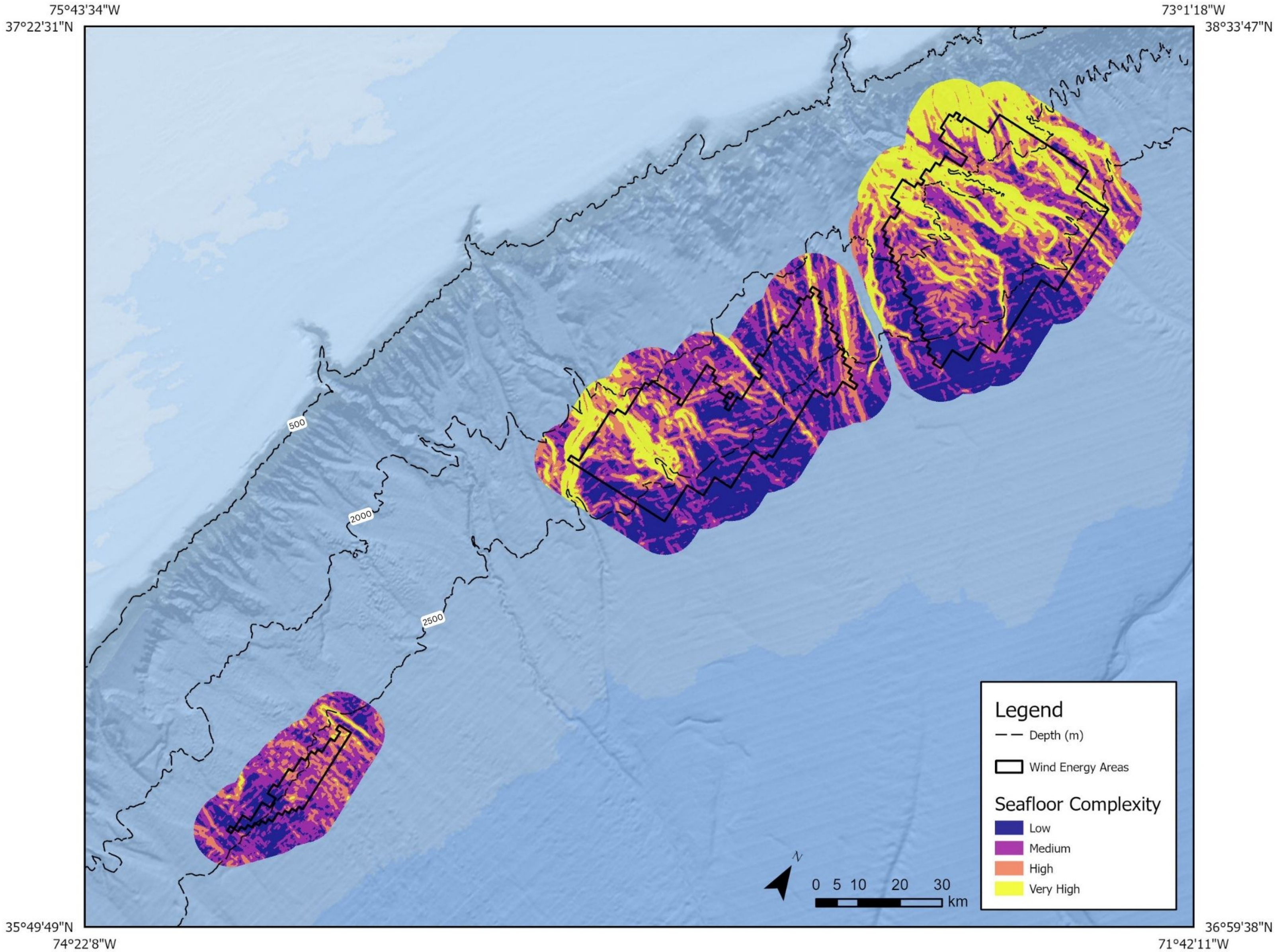

Figure 6: Raster Map 2 – seafloor complexity

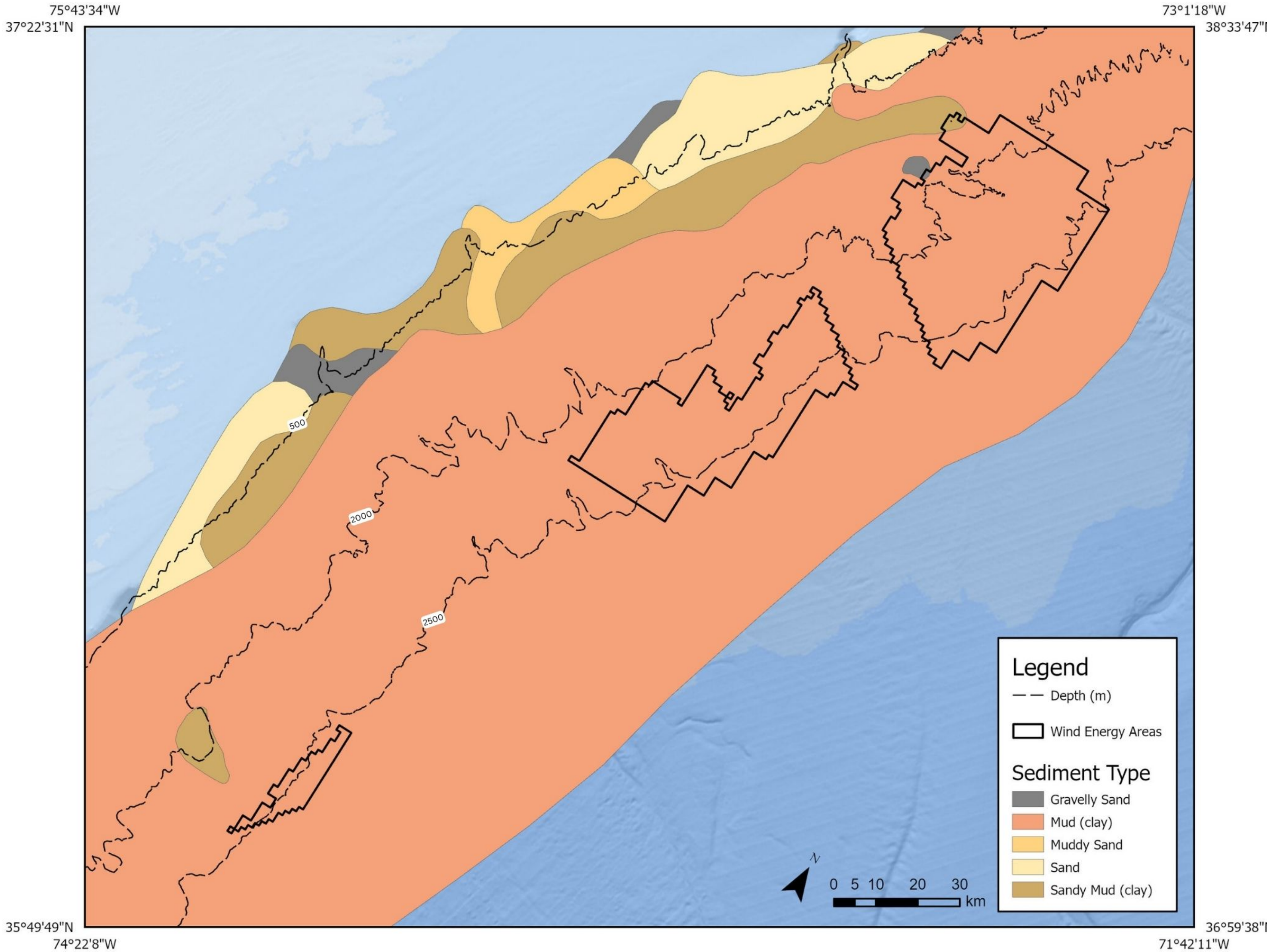

Figure 7: Raster Map 3 – sediment type

3.4 Weighted Overlay Modeling

The goal of this suitability analysis is to provide guidance in determining suitable locations for FOWFs within the designated draft WEAs in the Mid-Atlantic region. This method of modeling allows multiple outputs to be viewed and compared. For this thesis, five weighted overlay suitability analysis models were created for the draft WEAs. Through use of the Weighted Overlay tool, variable weights, which are proportional to importance, were applied to each input raster layer. The maps found in Chapter 4 show the overall suitability of the draft WEAs, highlighting areas from high to low suitability.

3.4.1 Reclassification

Prior to applying weights to the rasters and running the Weighted Overlay tool, the values in each dataset needed to be reclassified. Use of the Weighted Overlay tool requires that the reclassification be done on a common scale, meaning that each input raster had to have the same number of classifications. The remainder of this chapter explains how the raster data were reclassified for the suitability analysis.

3.4.2 Slope Gradient

The slope gradient data were reclassified based on the probability of slope failure. The probability of failure and gradient are directly proportional, signifying that higher gradients are associated with a higher likelihood of failure. To reflect that in terms of suitability of a location for development, lower bound values (less than 5°) are classified as most suitable, while higher bound values (greater than 10°) are classified as least suitable (Table 1). These bounds were selected based on data suggesting that slopes greater than 10° were likely areas of exposed rock.[26]

Table 1: Reclassification Suitability for Slope Gradient.

Reclassification of Bathymetry (Slope Gradient)			
Lower Bound (degrees)	**Upper Bound (degrees)**	**Reclass Value**	**Suitability**
0	5	1	High
5	10	2	Medium
10	100	3	Low

3.4.3 Seafloor Complexity

The original four classifications, presented in the raster map (Figure 6), contain complexity values ranging from 0 to 3. As previously mentioned, the Weighted Overlay tool requires a common scale, so the dataset was adjusted to meet that requirement. Values initially categorized as having a "very high complexity" were merged with "high complexity" values. Reclassification was then performed, modifying the scale to 1 to 3 (Table 2). Like with the slope gradient, the seafloor complexity is also inversely proportional to the suitability. Areas with higher complexity are deemed less suitable due to the presence of greater variability in seafloor features (e.g., valleys and peaks). Whereas areas with lower counts of seafloor features are less complex, and in turn, more suitable.

Table 2: Reclassification Suitability for Seafloor Complexity.

Reclassification of Seafloor Complexity		
Value	**Reclass Value**	**Suitability**
0	1	High
1	2	Medium
2	3	Low

3.4.4 Sediment Type

In the sediment raster map (Figure 7), five classifications are depicted in the AOI. After the Extract by Mask tool was utilized to create the 8 km buffer around the WEAs, only three classifications were observed. Those classifications, listed in Table 3 below, were denominated as low, medium, and high suitability. Sandy mud (clay) was ranked as the least suitable for FOWTs because sandy sediments have a higher risk of liquefaction. Gravelly sand, though still at risk of liquefaction, is not as susceptible to it as sandy mud (clay). The grain size of gravels and rock mixtures also have anchoring constraints, making them less suitable options. The third classification of mud (clay) is the most suitable, as it does not have anchoring constraints and its risk of liquefaction is minimal.

Table 3: Reclassification Suitability for Sediment Type.

Reclassification of Sediment Type		
Description	**Reclass Value**	**Suitability**
Mud (clay)	1	High
Gravelly sand	2	Medium
Sandy mud (clay)	3	Low

Chapter 4

RESULTS

The following maps display the results from the five suitability analysis models run for the draft WEAs using inputs of seafloor gradient, seafloor complexity, and sediment type. Lower values are more suitable for FOWTs, while higher values are less suitable. Each map also contains bathymetric contours at 500 m, 2000 m, and 2500 m for reference.

Table 4 describes the weight percentages applied to the input rasters in each model. Model 1 is an equally weighted analysis. Model 2 emphasizes the slope gradient, while minimizing the sediment type. In Model 3, seafloor complexity is the most important factor, while slope gradient is the least. Model 4 places more weight on the sediment type and minimizes the seafloor complexity. Finally, Model 5 splits the weight between slope gradient and seafloor complexity, while completely eliminating the effect of sediment type. This was done to account for the uncertainty and variability of sediment data.

Table 4: Suitability Analysis Weight Assignments.

Input Raster	Model 1	Model 2	Model 3	Model 4	Model 5
Slope Gradient	33%	50%	20%	30%	50%
Seafloor Complexity	34%	30%	50%	20%	50%
Sediment Type	33%	20%	30%	50%	0%

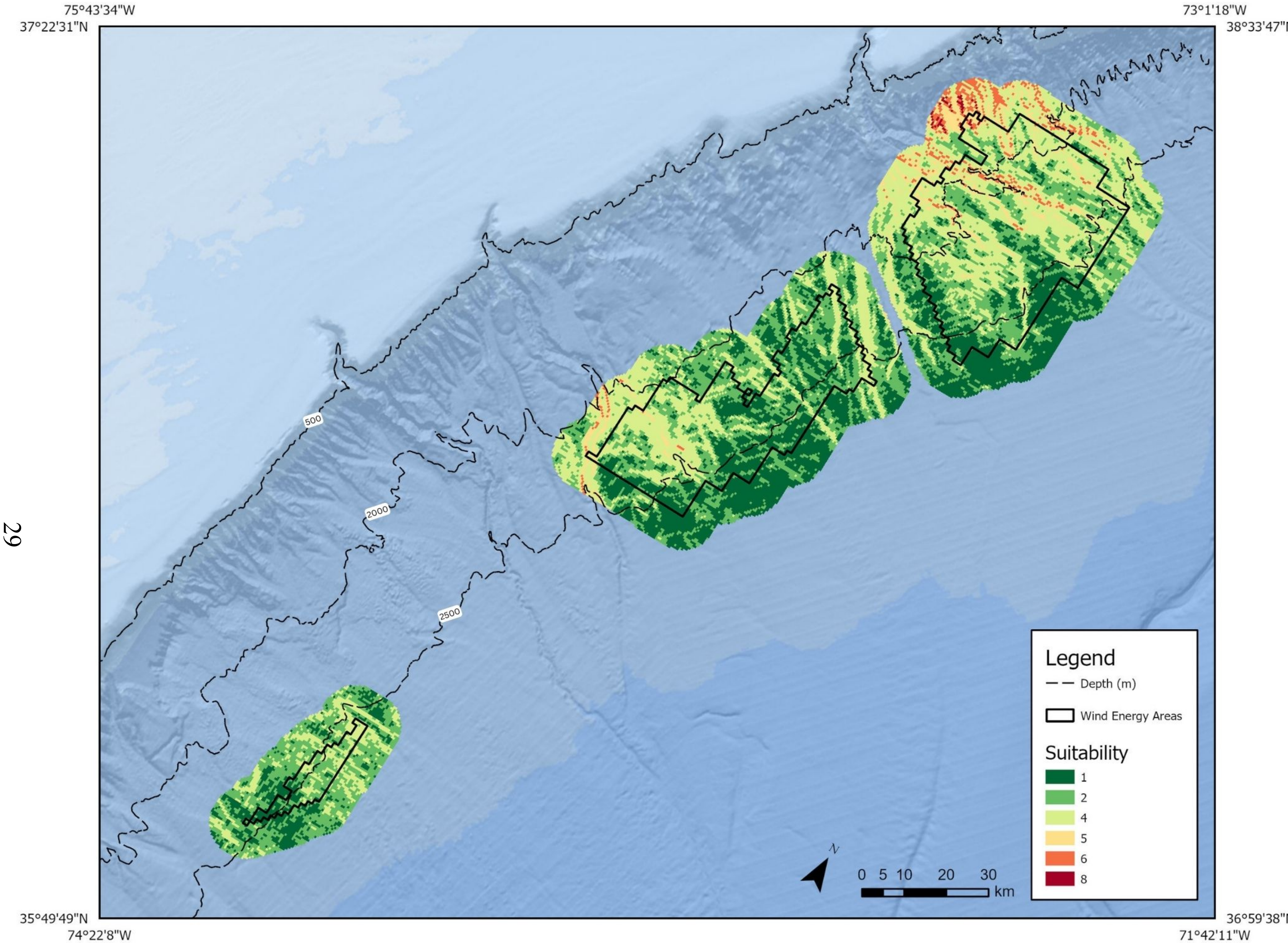

Figure 8: Suitability Model 1 – slope gradient 33% seafloor complexity 34% sediment type 33%

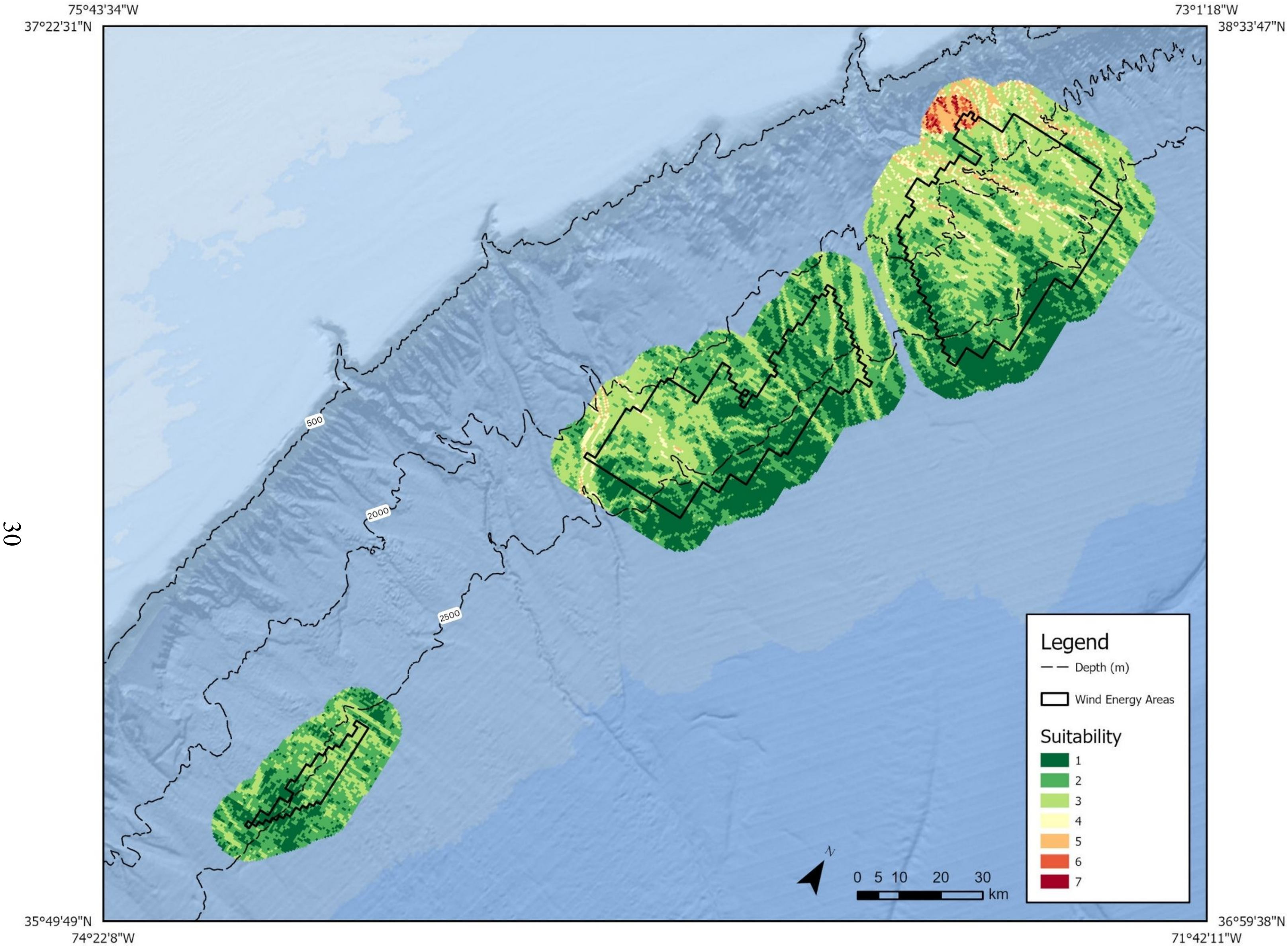

Figure 9: Suitability Model 2 – slope gradient 50% seafloor complexity 30% sediment type 20%

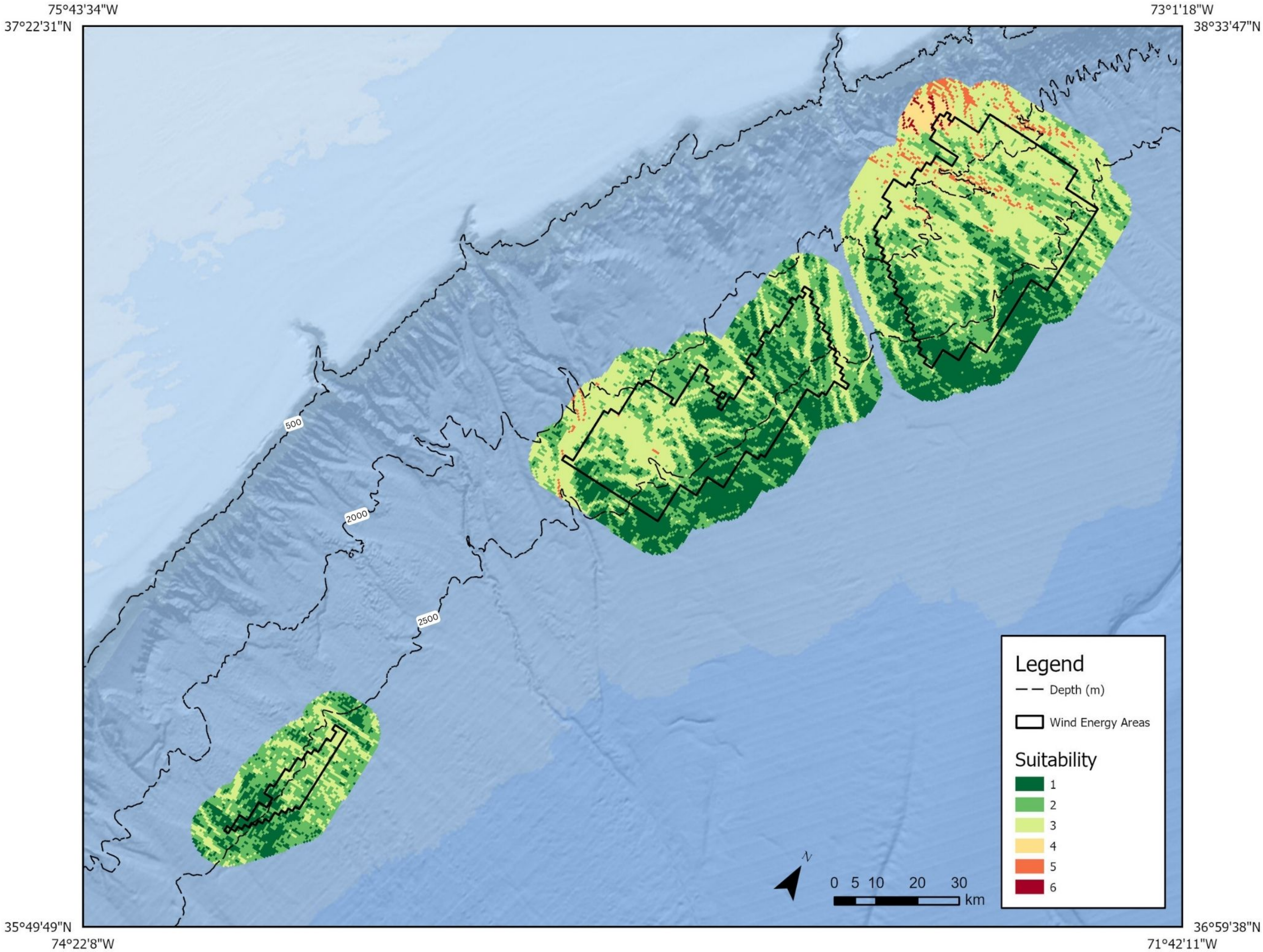

Figure 10: Suitability Model 3 – slope gradient 20% seafloor complexity 50% sediment type 30%

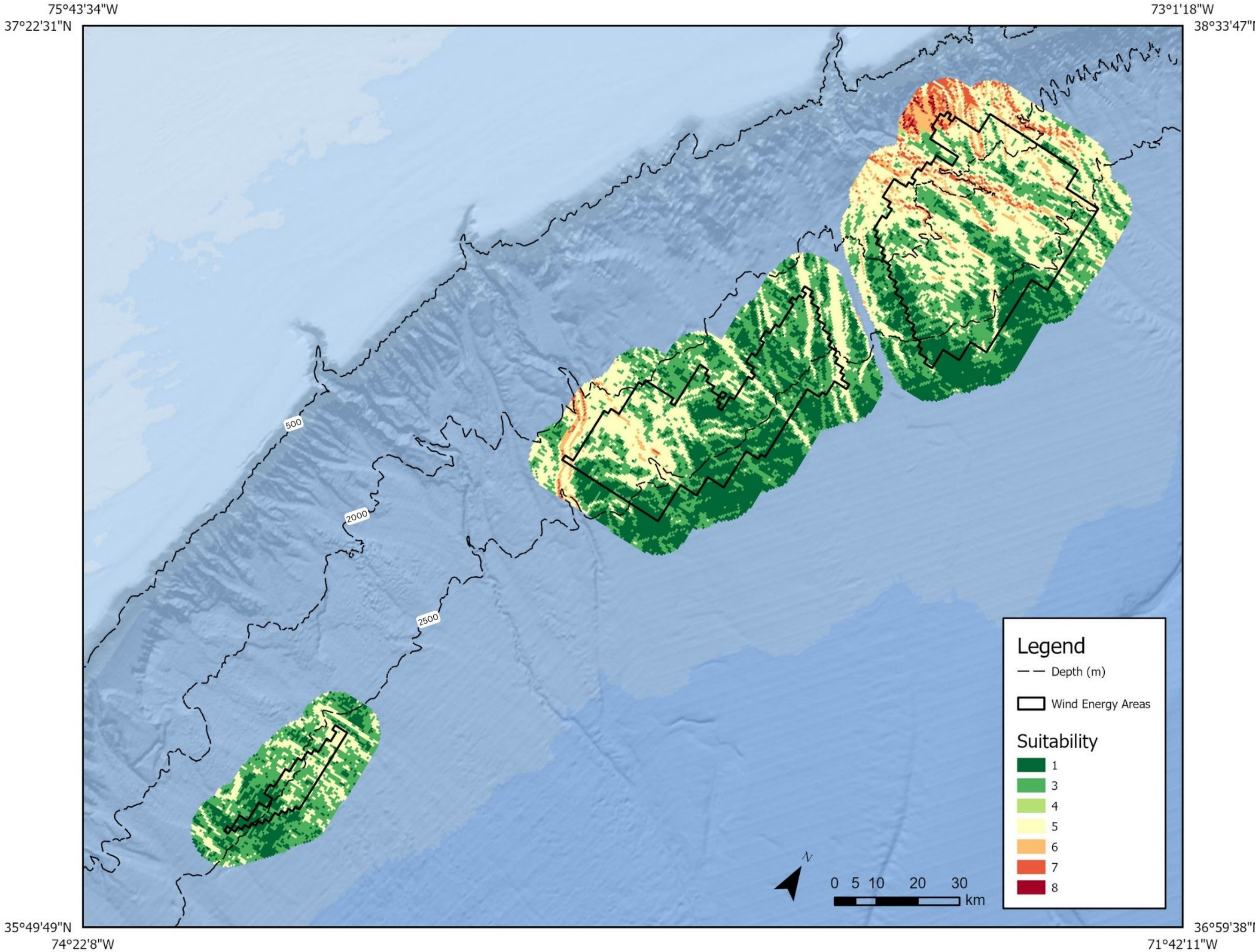

Figure 11: Suitability Model 4 – slope gradient 30% seafloor complexity 20% sediment type 50%

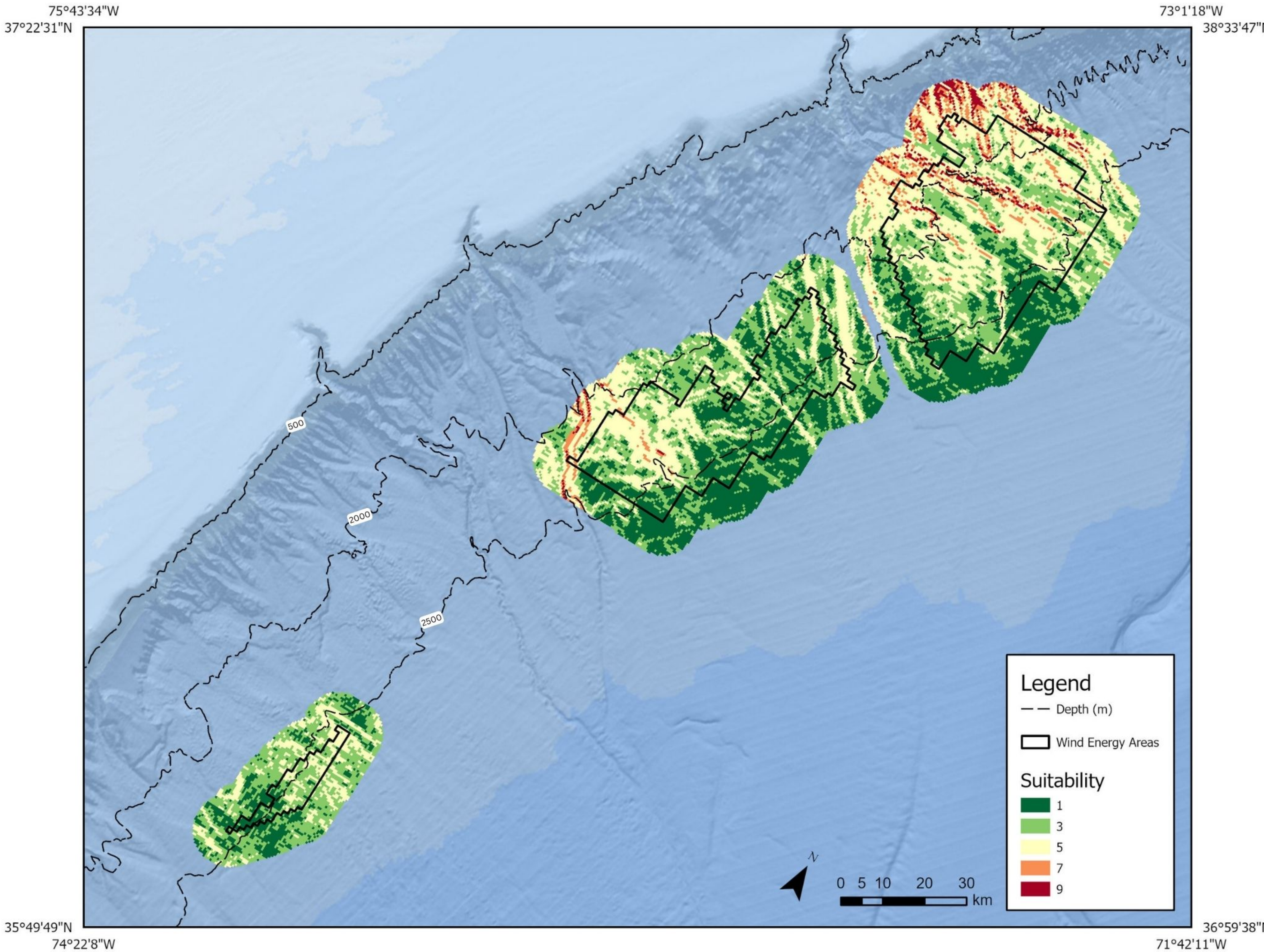

Figure 12: Suitability Model 5 – slope gradient 50% seafloor complexity 50% sediment type 0%

Chapter 5

DISCUSSION

The results of the suitability analysis indicate that all three draft WEAs are suitable locations for the deployment of FOWFs. Each WEA is discussed individually in this chapter, highlighting pros and cons of different locations within the areas.

5.1 WEA E-1

Perhaps the most complicated study area of the three, WEA E-1 encompasses the highest slope gradients and complexity values (Figure 5 and Figure 6). In the northern half of this WEA, the suitability models show an area of lower suitability that cuts across from the west to the east. The lower suitability here is due to an increase in complexity and higher slope gradients. The maximum recorded gradient in WEA E-1 is 35°, which is not optimal for the placement of anchors or mooring systems. Gravity anchors, because they are situated on the seafloor, function much more effectively when placed on a relatively flat seabed.[10]

Another noteworthy attribute of WEA E-1 is its proximity to several submarine canyons. The Wilmington, North Hayes, South Hayes, South Vries, and Baltimore Canyons all extend to the north-northwestern border of WEA E-1. Having any FOWTs installed close to a canyon greatly increases the risk of impact by potential slope failures. Particularly, the Baltimore Canyon, as mentioned in Section 2.3.1, contains evidence of mass wasting that places the canyon in a state of slope instability that is prone to failure at any time. If failure were to occur, it is not currently known how turbidity currents generated by mass wasting events affect turbines, but it is likely to be a negative one.

5.2 WEA E-2

Within WEA E-2, the results of the analysis show the location of suitable areas opposite that of WEA E-1. Whereas WEA E-1 is more suitable in the south than the north, WEA E-2 is more suitable in the north. Characterized by a moderately large zone of high complexity values, the southern half of this WEA would be more problematic for development. In addition, it is necessary to account for the large submarine canyon that extends out to the southwestern border of WEA E-2. The Washington Canyon, like the Baltimore Canyon, has geologic evidence similar to the Currituck Slide Complex. Without further exploration, current data indicates that the Washington Canyon is unstable, making the southern portion of WEA E-2 not a feasible location for FOWFs. However, the northern half is presumably a much more suitable option for FOWFs. It is characterized by lower slope gradients and is minimally complex.

5.3 WEA F

Even though WEA F has the smallest area of the three WEAs, it is arguably the most suitable. A big advantage to this location is the lack of submarine canyons in close proximity to the WEA. WEA F also has some of the lowest recorded slope gradients in the entire AOI, which should significantly simplify the installation process of anchors and moorings. The main negative characteristic for this WEA is the degree of variance of the seabed terrain and its complexity. The complexity increases from south to north in the WEA. This does imply that the southern portion of WEA-F is more feasible, however, when compared to other locations in the AOI, it does not make the north a poor choice. All in all, WEA F is a favorable site for the location of FOWFs.

5.4 Recommendations

While draft WEAs E-1, E-2, and F are generally satisfactory locations for the development of FOWFs, it is important to consider that sediments and seabed features may change over time. Ocean bathymetry is constantly evolving, meaning that sediments are constantly shifting. Depending on how dynamic the movement, the seabed may alter, and in turn, the complexity may change. The sediment data used in the suitability analysis presents muddy soil as the predominant sediment type for the WEAs. Note this does not signify that the WEAs consist of purely muddy soil, only that the collected samples were primarily identified as mud.

Prior to any offshore wind development in the AOI, additional samples are necessary for gaining a more comprehensive understanding of the sediment type. Collecting samples at each potential turbine location provides accurate soil conditions and is valuable for determining which anchor and mooring systems to utilize. Based on the sediment data used in the analysis, no one anchor or mooring type stands out as a leading option. However, suction pile anchors should be avoided in the presence of consolidated clays, as the resistance of clay makes them difficult to install. Otherwise, along with avoiding the use of gravity anchors near slopes – as previously mentioned, there are no real concerns for using one type of anchor or mooring over another.

Taking the submarine canyons into consideration is crucial for turbine placement within these WEAs. Supplementary geotechnical studies should be conducted to determine the potential of slope instability in the AOI. Any areas with evidence of mass wasting or sediment buildup on slopes should be avoided, as there is too much uncertainty surrounding possible negative impacts for wind turbine moorings. Foundation moorings in suitable locations that are further eastward places them farther away from the canyons. However, this also means that the turbines would be situated at greater distances from shore, which would require longer submarine cables, leading to higher installation costs and greater line loses.

The peak ground acceleration (PGA) is another valuable factor to account for with development on the continental slope and rise. PGA data provide insight on the risk of seismic hazard and how much effect seismic activity might have on a given location. Due to the lack of available data, PGA was ultimately left out of this study. Additional surveying is needed off the Mid-Atlantic shelf to obtain sufficient PGA data. Ideally, data should use a PGA metric for a 10% probability of exceedance in 50 years. This metric is favorable for long-term performance considerations, like the installation and operation of an offshore wind farm, as it signifies the expected ground acceleration that would occur during a 500-year earthquake.[11,22]

At end, there is no one optimal location for development of FOWTs in the Mid-Atlantic region. Even the more suitable locations come with risks, whether that be a result of the soil conditions, the slope gradient, the PGA, or any other seabed feature. More detailed assessments aimed at collecting data on these features is certain to increase confidence in development and raise the likelihood of success.

Chapter 6

CONCLUSION

The research presented in this thesis aimed to explore the suitability of FOWFs in the Mid-Atlantic region through the analysis of geological data displayed as suitability models for WEAs E-1, E-2, and F. These three deepwater sites, designated by BOEM on behalf of the Biden-Harris Administration, are located on the continental slope and rise with numerous submarine canyons close to their western borders. The suitability was based in part on the WEAs' proximity to submarine canyons, in addition to any potential hazards associated with the canyons. Hazards in the region include, but are not limited to, submarine landslides and slope failure triggered by seismic activity.

In addition to the presence of submarine canyons, data on the slope gradient, seafloor complexity, and sediment type were utilized to investigate the probability of geohazards in the region that could potentially impact floating turbines installed within the WEAs. Applying the Weighted Overlay tool in ArcGIS Pro, the data were assigned variable weights proportional to their importance. This method allowed for the rasters (slope gradient, seafloor complexity, and sediment type) to be evaluated together on a common scale.

The findings of the weighted overlay suitability analysis support the development of FOWFs in three draft WEAs. The models show the draft WEAs to be suitable locations, even with the presence of considerable submarine canyons in the region. Developers should still proceed with caution, however, as characteristics of the seafloor are subject to change with the ocean bathymetry with time. Based on the models in this thesis, WEA E-1 currently possesses the highest slope gradients and the greatest complexity values among the WEAs. That is followed by WEA E-2, and then WEA F with the lowest values.

Depending on the movement of sediment via turbidity currents on the continental slope and rise, in time, the suitability data may deviate from these results. That every bit of data utilized in this research is susceptible to change is a limitation worth considering. The suitability analysis is meant to provide guidance and awareness of what might be expected if a given WEA were to undergo development. That is why it is important that further geotechnical investigations be conducted prior to offshore wind development in the general deepwater Mid-Atlantic region.

Without the inclusion of PGA data, the analysis was unable to truly capture the impact of seismic activity for the area. This limitation was due to the weighted overlay requiring a common evaluation scale. PGA datasets for the Mid-Atlantic currently contain only two values, while the rest of the data used in the models have three. Assumptions were made about the potential negative effects of earthquakes, as well as the likelihood of increased risk near submarine canyons, but these assumptions alone cannot be relied upon. It is probable that the lack of data in the region is simply because surveys collecting PGA data have yet to be conducted.

Ultimately, looking at the big picture, FOWFs should be installed in draft WEAs E-1, E-2, and F. The data utilized in this research does not indicate a high enough risk of slope failure to be a real concern at this time. Having discovered where development is preferable within the WEAs, that is the substantial finding of this thesis. If developers are cautious and do their due diligence, deepwater offshore wind sites have potential to be highly successful in the Mid-Atlantic region.

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