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Application of Technology Development Index and Principal Component Analysis and Cluster Methods to Ocean Renewable Energy Facility Siting

for the Rhode Island Ocean Special Area Management Plan 2010

by

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Executive Summary

To assist in siting of offshore renewable energy facilities (wind, wave, and in-stream tidal and ocean current) a marine spatial planning based approach is proposed. The first level (Tier #1) screening determines the potential energy resource to be exploited and then identifies areas that are prohibited from siting because there is a direct, irreconcilable conflict, as determined by a stakeholder process and vetted by regulators. Areas that remain after these exclusions are implementeded are candidates for facility siting. The next step involves considering technical (engineering and economic) attributes of the proposed energy development that further restricts the area under consideration. Finally Tier #2 screening (not addressed here) evaluates other use conflicts such as recreational and commercial fishing areas, marine mammal feeding and breeding grounds and transit paths, bird migratory paths, feeding, and nesting areas, and similar that must be considered in facility siting.

To facilitate the application of technology constraints on siting, two methods are proposed, a Technology Development Index (TDI) and a Principal Components - Cluster Analysis (PCCA). The TDI method, developed by the authors and presented in this paper, is ratio of the Technical Challenge Index (TCI) to the Power Production Potential (PPP) of the energy extraction device. TCI is a measure of how difficult it is to site the device at a given location plus a measure of the distance to the closest electrical grid connection point. The PPP is an estimate of the annual power production of one of the devices. The site with the lowest TDI represents the optimum location. In practice, the study area is gridded and the TDI (TCI and PPP) is calculated for each grid. The method explicitly accounts for the spatial variability of all input data. Simulations can be performed either deterministically or stochastically, using a Monte Carlo method, so that uncertainties in the underlying input data are reflected in the estimated values of the TDI. The later approach allows detailed assessment of the sensitivity of the estimates to the input data and formulations of the TCI and PPP. The results are presented in the form of contours of TDI. The method can be applied to any offshore renewable energy type or extraction system once the technical attributes are specified.

The PCCA approach uses several spatially varying variables that describe the key attributes of the siting decision (e.g. water depth, power production potential, distance to shore, and seabed conditions). The principal components are first determined from the gridded data and then

clusters are identified. Finally the clusters are mapped to the study area. The attributes and spatial distribution of clusters provide insight into the optimum locations for development.

The two methods were employed in identifying potential areas for siting of a wind farm in coastal waters of Rhode Island, assuming lattice jacket support structures for the wind turbines. Both methods give consistent results and show locations where the ratio of technical challenge to power production is minimized.

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Abstract

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1 Background

Rhode Island's(RI) Coastal Resources Management Council (CRMC) is currently leading an Ocean Special Area Management Plan (SAMP) (http://seagrant.gso.uri.edu/oceansamp/) that will result in zoning of the state's coastal water to accommodate a wide variety of uses, including renewable energy development. In this effort, identification of sites for offshore renewable energy facilities (wind, wave, and in-stream tidal and ocean current) is being performed using a marine spatial planning based approach (geographic information system (GIS) analysis). The planning process is proceeding on an accelerated schedule and requires selection of those areas in the SAMP region where limited funds for site assessment should be focused. Basic level (Tier #1) analysis is therefore being used to identify those areas where detailed analysis on siting constraints and conflicts with other uses or ecosystem attributes is anticipated as being most valuable.

Methods for siting of offshore renewable energy facilities (wind, wave, and in-stream tidal and ocean current) have been under development for the past two decades in Europe but are just beginning in the US. The most well developed approaches (see Marine Resource Assessment System, MarS, used by the UK Crowne Estates as an example, http://www.thecrownestate.co.uk/mars) employ a multi-step, marine spatial planning protocol that develops geographic information system (GIS) maps of the energy resource and any constraints on siting of extraction facilities. This mapping and constraint analysis exercise identifies areas with conflicts in use and ultimately those with development potential. This is followed by a detailed sustainability and financial analysis for each development effort. The weighting methods used in performing these analyses are often treated as proprietary by the authority exercising control of the seabed and not available for review or evaluation.

In the US, offshore renewable energy siting studies (e.g. Cape Wind development in Nantucket Sound, MA, http://www.capewind.org/) have typically been led by the developer with evaluations of prime and alternative sites for the proposed facility. An assessment of the site selection process is performed as part of the environmental permitting process by either the US Army Corp of Engineers (for developments in state waters) or the Minerals Management Service (for federal waters). Since most state and federal waters are not explicitly zoned for renewable energy development the proposer has wide latitude in proposing prime and alternate sites. This approach does not lend itself particularly well to marine spatial planning and its promise to help protect and restore ocean ecosystems while minimizing negative impacts and conflicts from human activities.

The present paper outlines the basic first level (Tier#1) marine spatial screening approach used in the RI Ocean SAMP study, including the use of one new method (Technology Development Index (TDI)) and the application of a well known technique (Principal Component – Cluster Analysis (PCCA)) for assessing the technical aspects of the development. The overall strategy is outlined first and the TDI and PCCA described in detail. As a demonstration, the Tier #1 approach is applied to siting of an offshore wind farm in RI coastal waters, with particular emphasis on the results of the application of the TDI and PCCA. Extension to Tier #2 screening, using the same conceptual strategy is currently in progress and will be reported in subsequent publications.

2 Approach

To provide a framework to assist in siting of offshore renewable energy facilities (wind, waves, in-stream tidal currents, and mean currents) a marine geospatial screening analysis is proposed. The analysis is divided into two separate tiers. Tier #1 screening begins with an assessment of the energy resource to be exploited. This information is normally given in terms of the speed of the flow or the energy density. As an example, for wind and water currents the resource could be specified in terms of mean speed (m/sec) or mean flow energy density (kW/m^2), while for waves one might use the mean wave energy density (kW/m). The values are typically displayed as gridded data on the area of interest. For wind and water currents the values are normally presented at hub height of the extraction device. If the speed or energy density is below a specified limit then exploitation of the resource is not economically viable and hence no further analysis is required. These thresholds are dependent on the local cost of energy (with or without subsidies) and the state of technology development. Some commonly used, but not definitive thresholds are: wind speeds greater than 7 m/sec at hub height, water current speeds greater than 1.5 m/sec, and wave energy densities greater than10 kW/m. It is important to note that since the energy densities are generally low, a large number of devices (10s to 100s) are typically required to generate grid scale power. These devices are typically distributed over a large area given the need to minimize the interaction between extraction devices. As an example, the spacing for offshore wind turbines is on the order of 10 blade diameters in the principal flow direction and 6 blade diameters in the cross flow direction.

If the energy density is sufficient to warrant development then an analysis is performed to determine any constraints imposed by existing uses within the study area. As example, existing uses or restrictions might include regulated marine transportation areas (shipping lanes, precautionary areas, preferred routes, ferry routes), regulated uses (disposal sites, unexploded ordnance, marine protected areas and conservations zones, military areas), areas permitted /licensed for existing developments (oil and gas, offshore renewable, aggregate extraction, aquaculture), set backs from airports, and a coastal buffer zone. These might be viewed as strong or hard constraints since the two uses are incompatible. Note that other uses (occasional vessel traffic, impacts on view shed) might be viewed as weak or soft constraints that can be evaluated as part of a tradeoff study). Whether a constraint is considered hard or soft is normally vetted through a stakeholder process and ultimately subject to review by regulators. This analysis is performed by overlaying GIS layers for each of the uses, with each layer further reducing the area available for energy facility siting.

In the next step, two fully independent methods are proposed to help further narrow the viable areas: the Technology Development Index (TDI) and application of the widely known Principal Component - Cluster Analysis (PCCA) approach. The motivation for this step is to determine from a technical point of view which areas are most appropriate for development. Each method is explained separately below. As an alternative to the strategy above, it is possible to perform the TDI and PCCA analyses first and then the constraint analysis.

2.1 Technology Development Index (TDI)

The Technology Development Index (TDI) is defined as the ratio of the Technical Challenge Index (TCI) to the Power Production Potential (PPP). In brief, it gives an estimate of how difficult it is to site the energy extraction device relative to the power production potential if the device is sited at that location. The method is normally applied on a square grid that represents the study area.The grid resolution is dependent on the availability of input data.

$$TDI = TCI/PPP \qquad (1)$$

The minimum value of the TDI is the optimum siting location since it is the site with the lowest ratio of TCI to PPP.

$$PPP = W \times CF \qquad (2)$$

where

W- annual mean power density at the extraction site (kW/m or kW/m^2)

CF- capacity factor is the ratio (normally expressed in percent, %) of a power plant's actual production over a given period of time with the amount of power the plant would have produced if it had run at full capacity for the same amount of time (Justus et al, 1976; Hennessey, 1976). CF principally depends on the temporal characteristics of the energy resource and the power production curve for the extraction device. It inherently accounts for the intermittency of the energy source. Note that the CF adjustment in Equation 2 is not necessary, if CF is assumed constant over the study area.

In the case of offshore winds, W is the mean annual power density (kW/m2) at hub height and CF is approximately 35% (RERL, 2008). For waves, W is the mean annual power density in kW/m of wave front and CF is comparable to the value for wind. Additional factors could be considered in the formulation of PPP, such as power production during peak usage periods, if desired by the user.

TCI represents the technical challenge associated with the placement of a extraction device at a given offshore location and delivery of power to the electric grid. It has two major components; the first represents the support and foundation structure for the device and the second the distance from the site to the closest electrical grid connection point. The TCI for the support and foundation system is based on the technology type. The value may be adjusted to address the impacts of water depth, extreme wind and wave loading conditions, mooring constraints, the difficulty in installing the foundation (driving piles, drilling and grouting) and others. It is noted that the cost or technical challenge of the extraction device itself (wind turbine, in stream tidal current turbine, or wave energy conversion device) is not included in the analysis since it is assumed to be the same at all sites and hence does not contribute toassessing the differences between various sites.

The proposed formulation is:

$$TCI = TT + CD \qquad (2)$$

where

TT- Technology Type. The values here depend on the energy extraction system and its associated support structure and foundation system.

CD – Prorated Cable Distance (distance to the electrical grid x SF/number of energy extraction devices in the field) where SF is a scaling factor. This formulation prorates the technical challenge of installing the main power cable to shore over all extraction devices in the field. Cabling within the extraction device field is not included since it would be the same for any field of similar devices. The scaling factor weights the technical challenge of cable installation relative to the TT values used in the analysis. As an example, if the metric used in defining TT is monetary then SF is the cost of the cable per unit distance (Green et al, 2007) If the field contains a large number of devices (100s) CD is generally small compared to TT.

TCI can be estimated by numerical values assigned to each of the categories ranked in level of difficulty based on professional judgment (say 1 to 5, with 5 being the most difficult). Ideally TCI could be estimated from the structure design and installation and associated cost for a given location.

As an example of the later, Table 1 provides Roark's(2008) assessment of the relative costs with each technology type for mono-pile and lattice jacket based wind turbine support structures for varying water depths.

Table 1 TT values (cost) for mono-pile and lattice jacket wind turbine support structures as a function of water depth (Roark, 2008).

Mono-piles -	$ 2.9 M, water depths - 5 to 25 m, not viable in deeper water depths
Lattice Jacket –	$ 3.36 M water depths - 5 to 25 m
	$ 4.48 M water depths 25 to 45 m
	$ 5.76 M water depths 45 to 65 m

Comparable estimates for lattice jacket structures for the German North Sea AlphaVentus (30 m water depth) (Seidel, 2007) and Beatrice, Moray Firth, Scotland (42 m water depth) (Talisman Energy, 2004) projects are $3 M and $4.5 M, respectively and in reasonable agreement with the trends given in Table 1. Estimates in Table 1 might be adjusted to account for the effort required to install pilings to support the wind turbine. As an example, if the depth to bedrock is quite shallow, compared to the water depth, the TT values would be multiplied by a degree of difficulty to account for the increased technical challenges (drilling and grouting or alternatively vessel days on site) of installing the pilings. This multiplier could also be determined by cost.

In application, the TDI is calculated for a grid covering the study area. The resolution of the grid is typically dependent on the availability of input data. To minimize the computational effort, TDIs only need to be estimated where the energy resource is above the minimum threshold for power production and can exclude areas based on constraints imposed by the TT.

As an example, for a mono-pile based wind power device the mean wind speed at hub height must exceed 7 m/sec and the water depth be less than 25 m. Prediction of TDI can be made using discrete values at each site or performed as a Monte Carlo simulation where uncertainties in the input data can be approximated with an appropriate distribution function. The distribution functions may be different for different variables in the problem.

Model predictions are displayed in terms of the mean (and standard deviations if Monte Carlo simulations are employed) of the TDI for a given technology type. The TDIs can also be converted to non-dimensional form by dividing by the lowest possible TDI in the study area (the grid with the highest PPP, zero cable distance, and the lowest TT). (TDI in italics denotes the non dimensional form of TDI). The location of this site is really hypothetical since the highest PPP is not likely to be at the same position as the lowest TT. The non dimensional TDI values start at 1 and go higher, where values close to 1 represent optimum sites.

2.2 Principal Component – Cluster Analysis (PCCA)

Principal Component Analysis (PCA) is a mathematical procedure (Jolliffe, 2002; Zuur et al, 2007) that transforms a number of potentially correlated variables into a smaller number of uncorrelated variables called principal components. The first principal component accounts for as much of the variability of the data as possible and each succeeding component for as much of the remaining variability as possible. In practice the first several principal components account for most of the variability of the data. PCAs are often used in exploratory analysis of data and for developing predictive, data based models. They are typically used to reveal the internal structure of the data in a way that most simply explains the data variance.

The principal component data are then grouped into homogeneous clusters using the k-means clustering method (Lloyd, 1982 and Ding C. and X. He, 2004). In this approach, each cluster in the partition is defined by its member objects and centroid. The centroid for each cluster is the point from which the sum of distances from all objects in the cluster is minimized. The method uses Lloyd's iterative algorithm that minimizes the sum of distances from each object to its cluster centroid and over all clusters. Objects are relocated between clusters until the sum cannot be further decreased. The result is a set of clusters that are as compact and well-separated as possible and representative of the data. The clusters can then be mapped back to the grid from which the original data were obtained to develop a picture of the spatial distribution of the clusters.

3 Application

To demonstrate the approach, an application of the screening methodology, through the Tier #1 level, to siting of an offshore wind farm in RI coastal waters is presented. An earlier screening study for offshore wind development has been performed by RI Office of Energy Resources (ATM, 2007a, b). The present work is part of an Ocean Special Area Management Plan (SAMP) being developed for these coastal waters and an extension of the earlier ATM investigation. The study area is shown in Figure 1 and is bounded by the RI coast on the north, Connecticut and New York state borders (Long Island Sound) to the west, Massachusetts state border to the east (Buzzards Bay), and the outer boundary, 50 km offshore. The area includes Block Island Sound (western side) and RI Sound (eastern side) in their entirety. The state waters boundaries (3 mi, 5.6 km) are provided. The figure also shows contours of the water depth based on the NOAA bathymetric data (NGDC Coastal Relief Model. http://www.ngdc.noaa.gov/mgg/coastal/coastal.html).

Figure 2 shows an overlay on Figure 1 of the regulated areas that are considered to be hard constraints for siting of a wind farm. These hard constraints were vetted through a stakeholder process, with concurrence of the state and federal regulators. These include designated shipping lanes, precautionary areas, preferred navigation routes, ferry routes, dredged material disposal and unexploded ordnance sites, military areas, set backs from airports, and a coastal buffer zone. There are no marine protected areas and conservations zones, or areas permitted /licensed for existing developments (oil and gas, offshore renewable, aggregate extraction, aquaculture) in the study area. The data for each of these regulated areas was acquired from the NOAA Electronic Navigation Chart data base (http://www.nauticalcharts.noaa.gov/mcd/enc/index.htm). While cable routes and areas are provided on the NOAA ENC's they are not included here since the cable locations are well mapped and not considered a conflict with siting of wind turbine support structures.

3.1 TDI Method

The TDI was estimated on a 100 m square grid covering the study area. PPP was determined at a proposed hub height of 80 m using AWS True Winds wind speed data (Brower, 2007) by interpolating wind speed data from model predictions made at heights of 70 and 100 m. The friction coefficient (Hsu et al, 1994) is estimated at each grid cell from AWS data at those two levels. The value is approximately constant at 0.134. Figure 3 shows the contours of wind speed for the study area. The wind speed data was then converted to wind power per unit area of the wind turbine. While the mean wind speed increases gradually with distance offshore, from 7 to 9.6 m/sec, 37%; the wind power increases by a factor of 2.6. Grilli and Spaulding (2009) have performed a detailed comparison of model predictions to observations in the study area. The difference between predictions and measurements is normally distributed with an average value of about 0.17 m/sec and a standard deviation of 0.13 m/sec.

The TT for each location was estimated using the data in Table 1, assuming use of lattice jacket support structures for the wind turbines. The data in the table were fit with a linear regression with water depth. The water depths (Figure 1) were obtained for the NOAA gridded bathymetric data. In this case, the cable length was assumed to be the closest straight line distance to shore and the field to contain 70 wind turbines. The scaling factor was set at 0.8 (Green et al, 2007).

Figure 4 provides a contour map of the non-dimensional TDI for the study area. The TDI varies from 1 to 2.1. The large scale pattern shows that the TDI decreases with distance from the coast, displays a broadly distributed minimum and then increases with further distance offshore. Near the coast the TDI is high because the wind energy available is low, this in spite of the fact that the water depths are generally low. TDI decreases with continuing distance off shore because the wind energy is growing substantially, even though water depth continues to increase. Near the outer boundary of the study domain the wind energy has reached its maximum and begins to level off (seaward of coastal boundary layer), while the water depth continues to increase, and hence results in increasing TDIs. Variations from this large scale pattern are principally a result of the bathymetric variations near the RI coast, south and west of Block Island, and the shallower area in the vicinity of Cox's Ledge and Southwest Shoals (Figure 1).

Sensitivity studies were performed varying the number of turbines in the wind farm and to alternate paths for the cable. These simulations showed that the TDI only became sensitive to variations in CD if the number of turbines in the farm was small.

The effort (and cost) of installing lattice jacket structures is known to be sensitive to composition of the seabed sediments within the upper 30 to 50 m of the sediment column, since piles used to provide the foundation for these four legged structures are typically driven into the seabed at depths comparable to the water depth. The piles are typically either driven or drilled into the sediments/bed rock depending on the geotechnical properties of these materials.

The seabed geology in the study area is dominated by glacial end moraine and lake floor sediments deposited in several incidents of glacial advancements and retreats. A broad summary of the deposits within the upper 50 m of the sediment column is provided in Figure 5. This map is based on the analysis of Stone and Borns (1966), Schafer and Hartshoren (1965), Stone and Sirkin (1996) and Sirkin (1982, 1996). Using this map and sub-bottom survey data collected by Needell and Lewis (1984) in Block Island Sound and Lewis and Needell (1987) in eastern Long Island Sound and smaller scale sub bottom mapping efforts in RI Sound by McMullen et al (2008), a construction effort (geology challenge) map (Figure 6) was developed by glacial geological experts familiar with southern RI waters (J. King and J. Boothroyd, personal communication). The effort was ranked on a scale of 1 to 5. A low ranking indicates deposits amenable to pile driving operations, while the highest values reflect areas with shallow depth to bed rock requiring drilling and grouting techniques to install the piles. Intermediate values (level 3) are indicative of complex end moraine sediment deposits, consisting of a mix of lake-floor sediments, and sand, gravel, and boulders of varying size. Lacking any detailed site specific data the TTs were multiplied by a factor varying from 1 (for Construction Effort Level 1) to 2.3 for Construction Level 5. Variations at intermediate construction efforts were by determined by linear interpolation with construction effort. The construction effort maps are initial estimates and will be refined as additional sub-bottom mapping and geotechnical studies are completed.

Figure 7 shows the TDI when the construction effort effects on the TCI are included. As expected the broad scale pattern remains the same as for the case with no consideration for geology (Figure 5). The range of TDI has however increased from 1 to 2.1 to 1 to 3.5. The largest values are found in the areas of highest construction effort (see area south of Sakonnet Pt in particular). In the end moraine sediments, the values are higher than for the no glacial geology case because of the intermediate values for construction effort. The optimum (lowest TDI) site in state waters is the shallow areas south and southwest of Block Island (Figure 1). For federal waters the optimum site, if distance to shore is considered, is the deep water tongue located between two end moraine deposit sequences (Figure 5) just landward of Cox's Ledge-Southwest Shoals (Figure 1) in the center of RI Sound.

To understand the impact of uncertainties on the analysis, Monte Carlo simulations were performed to estimate the TDI. The uncertainty in the wind data was assumed to be normally distributed with an average value of about 0.17 m/sec and a standard deviation of 0.15 m/sec (Grilli and Spaulding, 2009). The uncertainty in TT was assumed as a top hat distribution, 15% higher and lower than the values reported in Table 1. The depth data was assumed to be accurate as provided. One hundred simulations were performed to assure an accurate estimate of the mean and distribution of the output. Figure 8 provides the predicted mean, and upper and lower 95% confidence limit TDI. These results can be directly compared to the deterministic case (Figure 7).

The TDI ranges are observed to be largest for the upper 95% confidence limit (1 to 10), smallest for the lower 95% confidence limit (1 to 6.4) and intermediate for the mean case (1 to 6.9). This compares to a range of 1 to 3.5 for the deterministic case (Figure 7). Independent of which analysis is evaluated the differential in TDI across the study area are preserved and identify the most appropriate sites.

In summary, the TCI increases with distance offshore since water depth generally increases with distance and hence the height (size) of the structure and length of support piles driven/drilled into the seabed increases and the distance to the closest grid connection increases. On the other hand, the wind energy (PPP) increases rapidly with distance offshore (Figure 3) as land based roughness effects on the atmospheric boundary layer decrease. This leads to a TDI saddle point (TDI minimum) at an intermediate distance offshore. Topographic variability alters this basic balance as does the effort of driving piles in end moraine and glacial lake deposits characteristically present in the area. The TDI method provides estimates that are robust to variability in the input data and is an objective and quantifiable method to facilitate this intermediate stage of site identification.

3.2 PCCA Method

The PCA analysis method was applied to the study area using the same grid as for the TDI method. The principal component analysis determines the new orthogonal/independent axes (u_i) with each being a linear combination of the original variables (y_i). For the present application four variables (y_i) were used for each grid: h- water depth, W- wind power, CD- distance to shore, and E - construction effort. Table 2 provides the coefficients for the first two principal components.

Table 2 Dependence for the first two principal components (ui) on the initial four variables (yi) (W- wind power, CD-distance to grid, h- water depth and E- construction effort). A linear fit is assumed.

	u_1	u_2
y_1 (W)	0.5	-0.43
y_2 (CD)	0.52	0.38
y_3 (h)	0.48	-0.57
y_4 (E)	-0.49	-0.58

Application of the method showed that 70, 90, and 98% of the cumulative variance of the original data could be explained by the first, second, and third principal components, respectively.

The data were mapped to the first two principal components domain and from visual examination five clusters were a-priori assumed as a desirable partitioning. Given the five clusters, the k-means clustering method was used to extract the most appropriate clusters to minimize the variance within a cluster and maximizing the variance between cluster centroids. Figure 9 shows the clusters mapped to the first two principal component domain.

Table 3 shows the major attributes of each of the five clusters in terms of the four input variables. The dependence on each is noted in qualitative terms. None of the clusters explicitly represent the optimum for siting of a wind farm. Clusters 1 and 2 however are best, 3 and 5 worst, and 4 is intermediate.

Table 3 Qualitative summary of the major attributes of each cluster in terms of the four input variables.

	Wind Power	*Depth*	*Distance*	*Construction Challenge*
• Cluster 1	Highest	Deep	Far	Low
• Cluster 2	High	Mid	Mid	Low
• Cluster 3	Lowest	Shallow	Close	Mid
• Cluster 4	Mid-High	Mid	Mid	Mid-High
• Cluster 5	Mid-Low	Shallow	Close	High

Figure 10 shows the clusters mapped to the study area. The cluster distributions are primarily oriented in the long shore direction and banded from near shore to offshore. The most desirable sites are located at intermediate to far distances offshore and the least desirable sites close to the coast (see area off Sakonnet Pt). The impact of water depth and construction effort is clearly seen. Visually the basic pattern in the cluster distribution and identification of the most appropriate sites for wind farm development are fully consistent with the prior TDI analysis; the TDI minimum and Cluster 1 and 2 are in the same general locations. To quantify this visual comparison , mean and standard deviations of TDI values were estimated for each cluster (Table 4). The analysis shows that Clusters 1 and 2 have the lowest TDI (1.7 to 1.8), with the smallest standard deviations (0.18 – 0.19). TDIs for Clusters 3 and 5 are highest (2.7 to 2.8) and have the highest standard deviations (0.41 to 0.6). Cluster 4 has an intermediate TDI mean (2.4) and standard deviation (0.26). This quantitative analysis shows that the cluster analysis maps are statistically consistent with the TDI analysis.

Table 4 Mean and standard deviation of TDI for each cluster (see Table 3 for definitions of clusters).

TDI	C1	C2	C3	C4	C5
Mean	1.8	1.7	2.7	2.4	2.8
Std Dev	0.18	0.19	0.41	0.26	0.6

3.3 Other Considerations

To develop a sense of the impact of view shed considerations on siting, an analysis was performed where the size of the coastal buffer zone was progressively increased to 8, 10, 12, 15, and 20 km from all land masses (Figure 11). This progression explores decreasing visualize impact of wind turbines in the field, with the 20 km offset approaching the limit of visibility.

To further consider the impact of marine transportation (in and outside of regulated areas) on siting, Automated Information System (AIS) data was obtained for the study area for Sept 2007 to July 2008. The US Coast Guard mandated AIS provides vessel track data on all commercial traffic in the study area, for vessels with lengths greater than 20 m, with the exception of fishing vessels. Figure 12 shows a plot of vessel traffic density (1 km resolution grid) over the observation period in terms of number of vessel counts. Areas that have fewer than 24 counts are not shown. The high count areas are observed in the in- and out-bound shipping lanes to Narragansett Bay, the precautionary area at the mouth of Narragansett Bay, the preferred east-west coastal transport route from Buzzards Bay, through RI and Block Island Sound, to Long Island Sound, and a route from the eastern end of Long Island Sound, through the Southwest Ledge channel, and then southwest parallel to the coast of Long Island.

Constraints can be imposed on marine traffic (AIS data), TDI levels, and coastal buffer distances to progressively refine site selection and to optimize for specified siting criteria. As an example, Figure 13 shows the impact of marine traffic restrictions. The upper panel shows the TDI map with no restrictions as a reference, the center panel, restrictions for exclusionary areas, and the lower panel, restrictions for exclusionary areas and areas with AIS counts greater than 24. Figure 14 shows the impact of restrictions on the TDI. The upper panel is once again the TDI map with no restrictions, the center panel, removal of areas with TDIs greater 3.0 (as well as exclusionary areas and AIS counts greater than 24) and the lower panel, the same as the center panel but with TDIs greater than 2.5 excluded. Finally, Figure 15 shows the impact of visual buffers. The upper panel is the TDI with no restrictions, the center panel, a visual buffer of 10 km (as well as exclusionary areas and AIS counts greater than 24), and the lower panel, the same as the center panel but with a visual buffer of 15 km. It is clear that this systematic process can identify sites that minimize TDI, impacts on marine transportation, and visualization. The map overlays also provide a methodology for assessing tradeoffs given varying constraints.

4 Conclusions

A marine spatial planning based screening method to facilitate siting of offshore renewable energy facilities has been presented. This basic strategy has been used for siting of other activities in the Ocean SAMP study area (dredged material, Battelle, 2003) and is an obvious candidate for the present application. Development and application of the TDI and PCCA methods have provided new quantitative tools to assist in the site selection process and in helping to identify and rank locations where facilities can be placed to minimize the technical challenge and maximize the power production potential.

Tier #1, of the two tier screening method, incorporating both the TDI and PCCA analysis methods, has been applied to siting a wind farm in coastal RI waters, as a demonstration case. The approach provides a logical step by step procedure to identify sites and to assess the impact of each input parameter on site selection. It is encouraging that both the TDI and PCCA methods provide consistent results on site selection even though the methods are dramatically different.

The first relies on a fundamental understanding of the development process while the later is based exclusively on the data. The very good agreement, as shown by a statistical comparison between the two, is, in part, due to the selection of parameters used as input to the PCCA. These are consistent with those used in the TDI. The TDI is preferred when TT is well known. The PCCA is very useful when the basic attributes of the energy device are not known. Its performance however is strongly dependent on the assumed input variables. The results of the TDI method are only as good as the input data and the formulation of the basic model. In the demonstration case, bathymetry and distance to the electric grid are judged to quite good. Wind power distribution data for this application is reasonable based on detailed comparisons to wind observations (Grilli and Spaulding, 2009). The seabed sediment maps are broadly consistent with the glacial geology of the study area. Interpretation of the seabed stratigraphy and associated construction effort map is supported by extensive sub-bottom profiles in Block Island Sound (Needell and Lewis, 1984), with penetration to 30 to 50 m or bed rock. There is however, very limited sub-bottom profile data for RI Sound.

The formulation for TT is based on data from a study reported by Roark (2008). The basic dependence of TT on water depth appears reasonable and consistent with data from AphaVentus (Siedel, 2007) and Beatrice developments (Talisman Energy, 2004). Additional validation needs to be performed. Work is progress in the European Mangrove Project (van der Tempel et al, 2008) to evaluate the cost for alternative structures for deep water applications. ODE (2007) and Papalexandrou (2008) have also evaluated costs of offshore wind farm development for varying turbine sizes, water depths, and foundation types. The formulation should also explicitly accounts for environmental loading from both extreme winds and waves. Hensel (2009) has recently developed a formula for TT as a function of structure and foundation weight for various soil conditions, based on sophisticated models for both the structure and foundation. The agreement with Roark (2008) is very good for the sandy soil case. Hensel’s (2009) analysis considers sand, soft and stiff clays soils. In assessing the impact of pile driving or drilling operations in various sediment types a simple scaling protocol has been used. This estimate can be substantially improved if additional knowledge of the sea beds sediments (including cores) in the study area were available.

Extension of the basic strategy presented above is currently in progress for Tier #2 screening. An Ecosystem Services Value Index (ESVI) methodology is being developed that quantitatively measures the ecological services for natural resources located in the study area. Initial work on the ESVI approach has clearly demonstrated that it will be difficult to develop a robust, numerical based planning tool given the lack of consensus on evaluation metrics and the absence and uncertainty of the input data required for the evaluation.

The TDI, PCAA, and ESVI should be viewed as new tools that will assist in an integrated, multi-disciplinary MSP process to assist in siting of renewable energy facilities.

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Jon Boothroyd, Geosciences and John King, Graduate School of Oceanography, University of Rhode Island provided the background information on glacial geology and generated the construction effort map. The project was supported by the RI Ocean SAMP project, led by Grover Fugate, Director Coastal Resources Management Council. The RI Ocean SAMP was funded by the RI Renewable Energy Fund.

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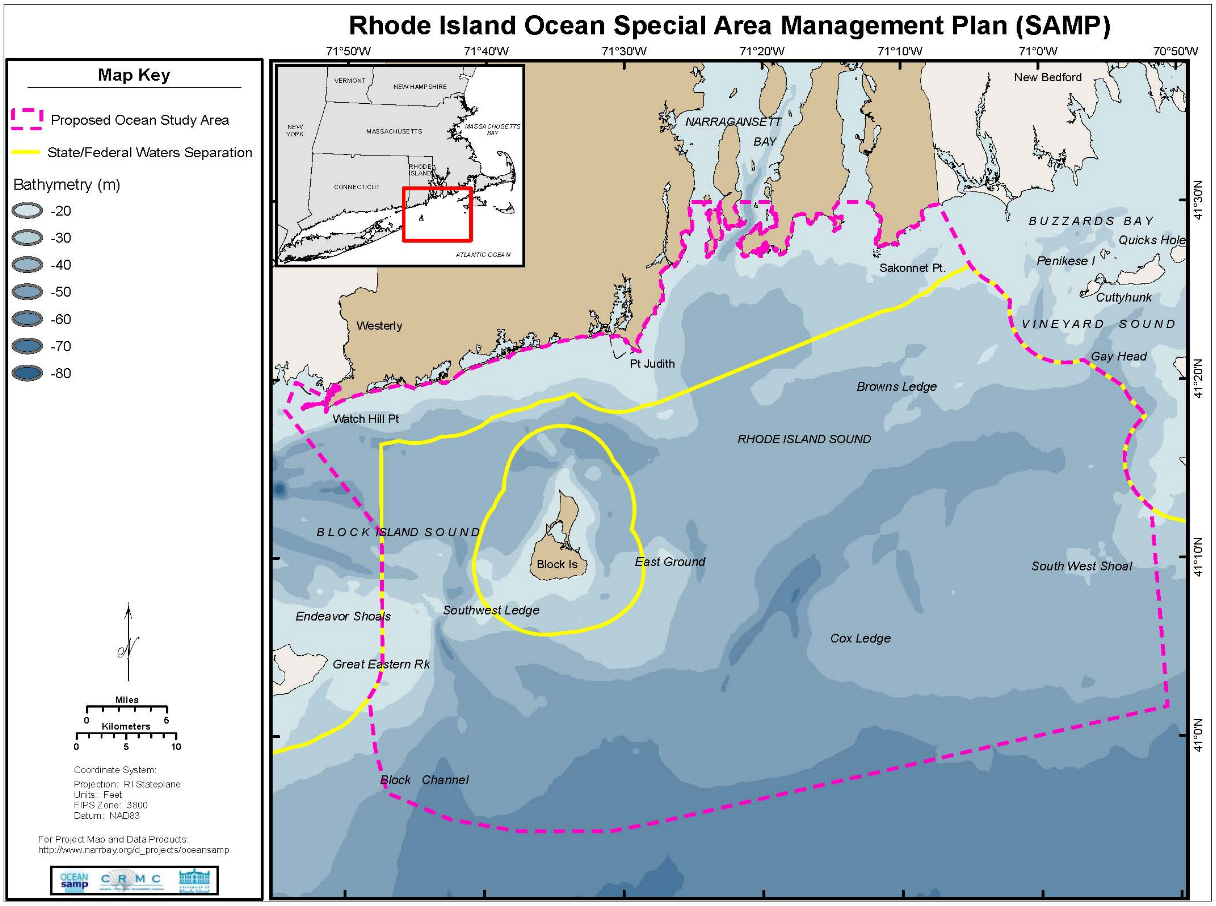

Figure 1 RI Ocean SAMP coastal study area. The dashed line is the study area boundary and the solid yellow line is the boundary of state waters. Key location names are provided as well.

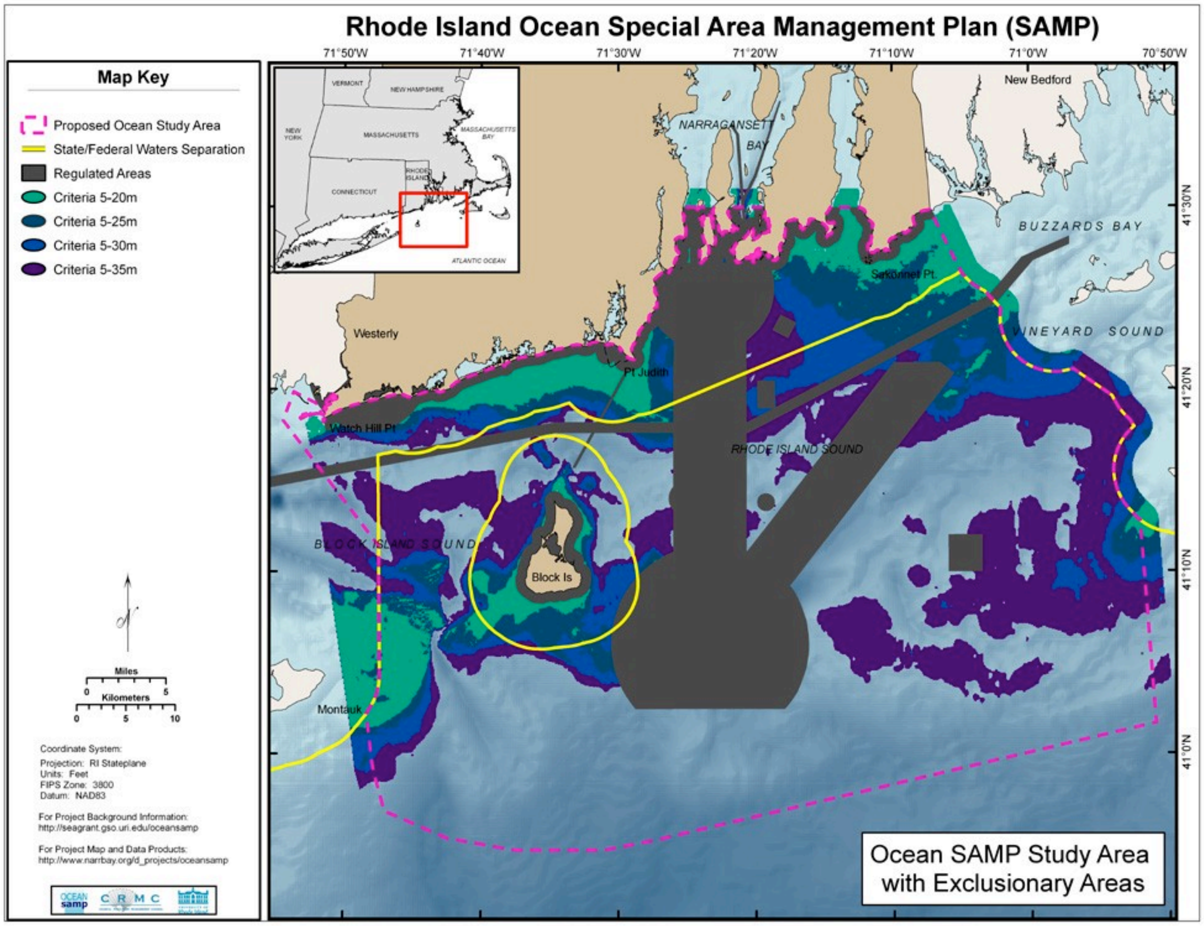

Figure 2 Study area with exclusionary areas (designated shipping lanes, precautionary areas, preferred navigation routes, ferry routes, dredged material disposal and unexploded ordnance sites, military areas, set backs from airports, and a coastal buffer zone) overlaid.

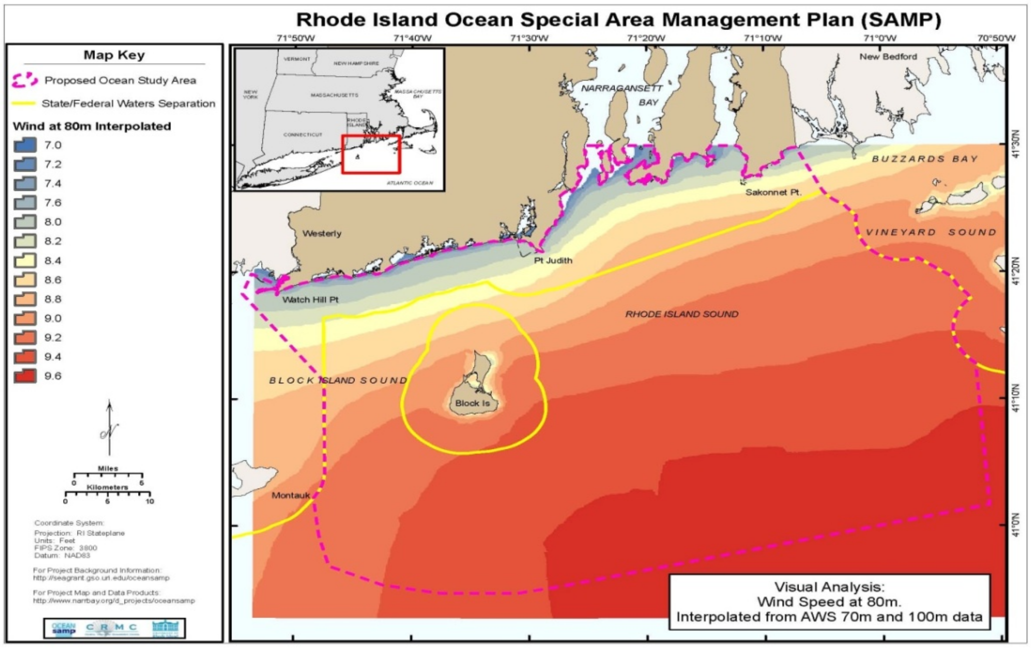

Figure 3 Wind speed contours at 80 m elevation interpolated from data at 70 and 100m from AWS True Solutions (Brower, 2007).

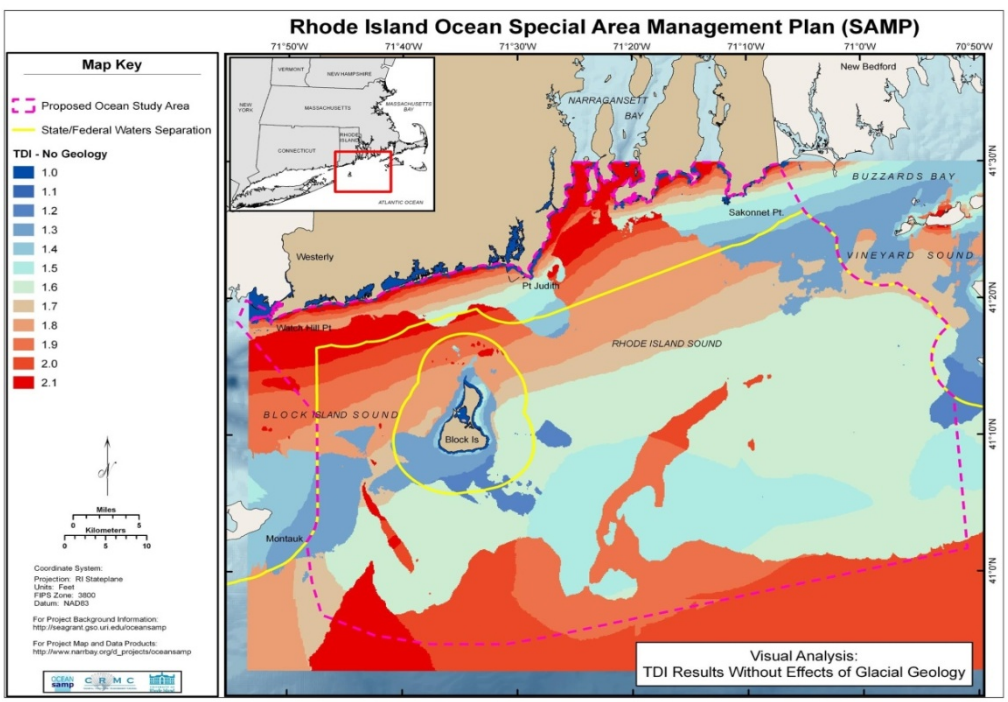

Figure 4 Contours of non-dimensional *TDI* for the study area, without glacial geology.

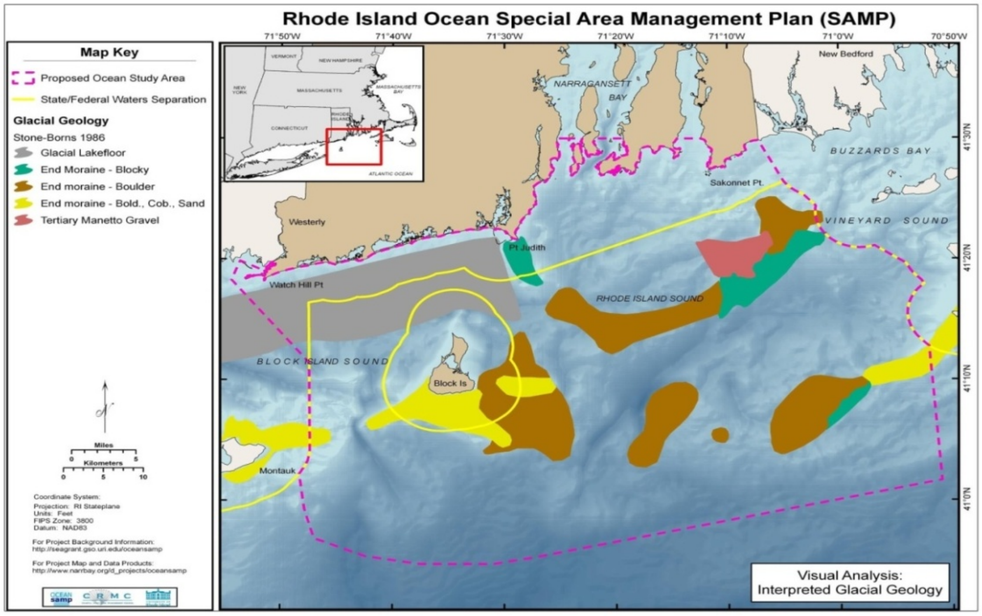

Figure 5 Glacial geology of the study area based on Schafer and Hartshorn (1965), Stone and Borns (1986), Stone and Sirkin (1996), and Sirkin (1982, 1996). Glacial lake floor, end moraine (blocky, boulder, cobble, and sand), and tertiary mannetto gravel deposits are shown.

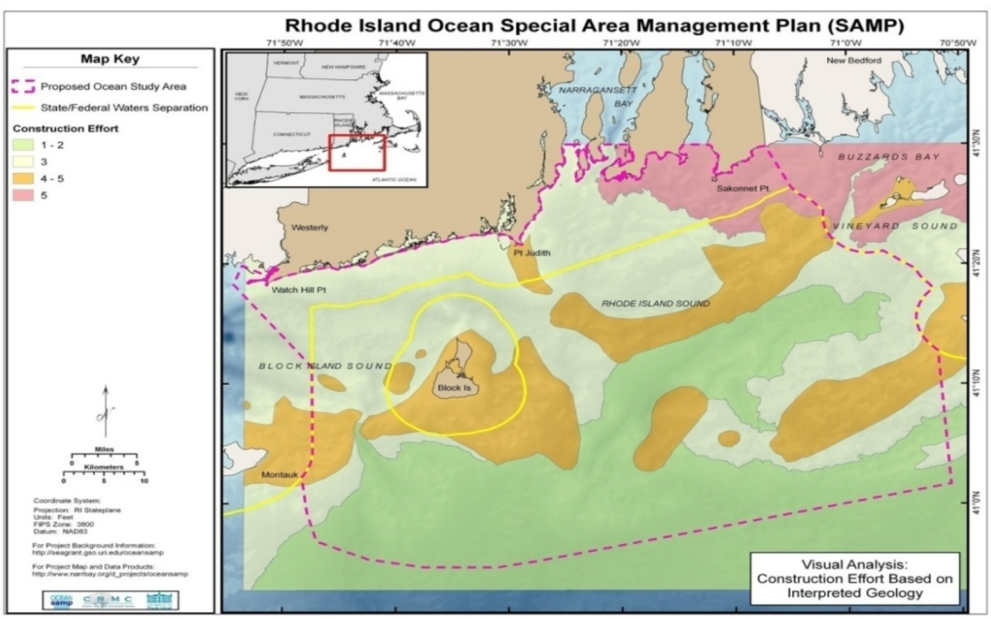

Figure 6 Estimates of the level of construction effort based on the glacial geology (Figure 5) and US Geological Survey (USGS) sub-bottom profile data (Needell and Lewis, 1984). Scale is 1 to 5, where 1 is lowest and 5 is the highest. Prepared by J. Boothroyd, Geosciences, and J. King, Graduate School of Oceanography, University of Rhode Island.

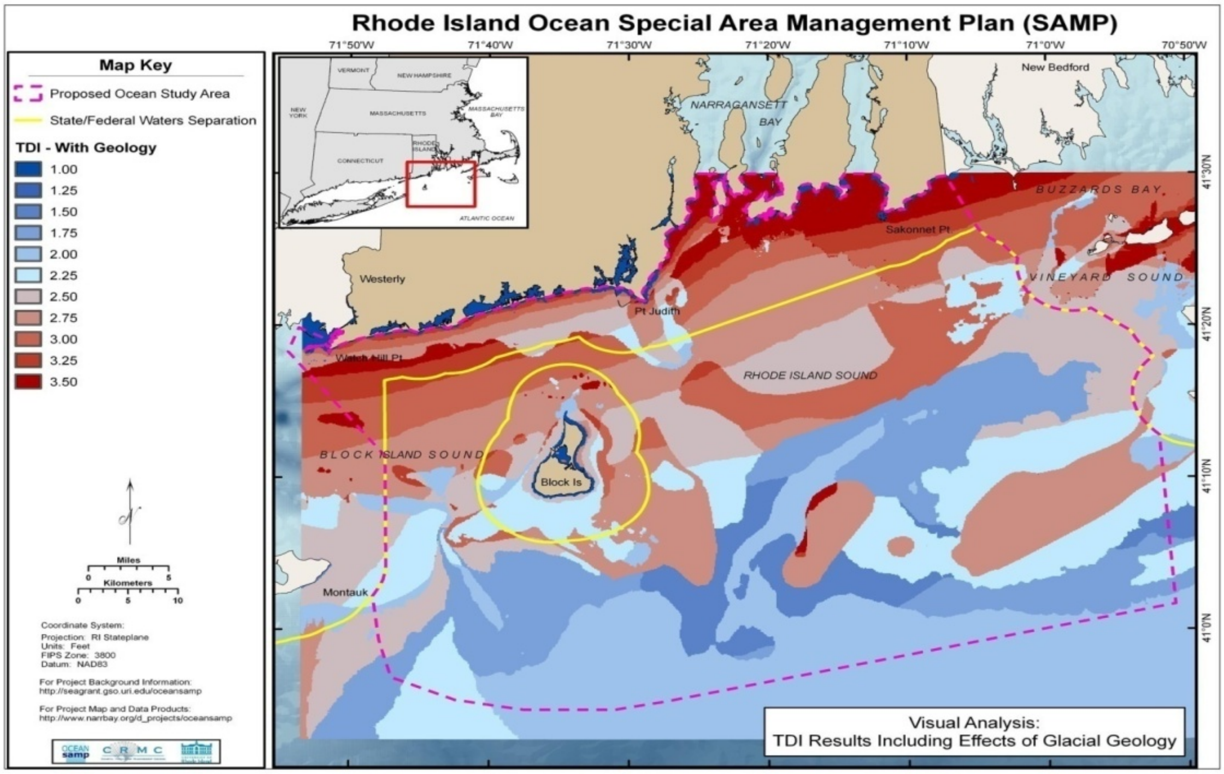

Figure 7 Contours of non-dimensional *TDI* for the study area, with glacial geology.

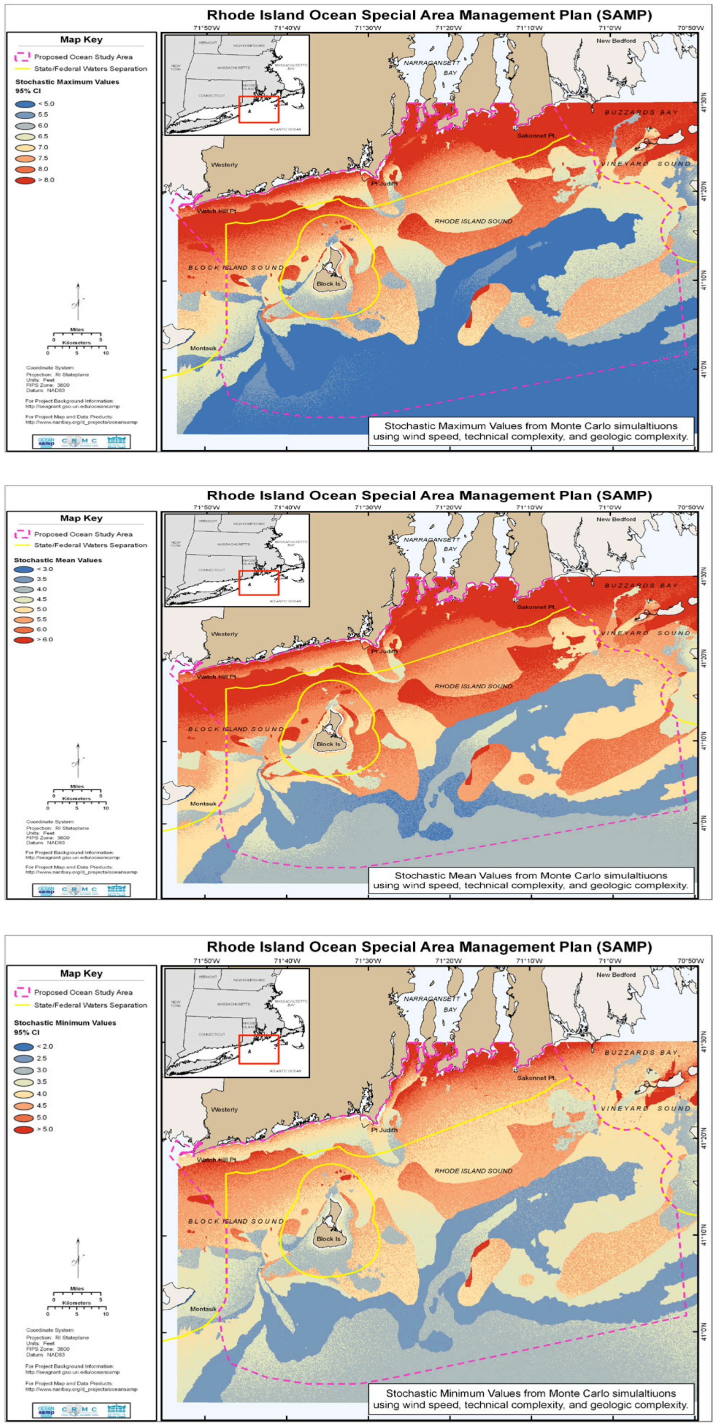

Figure 8 Contours of the non dimensional *TDI* with glacial geology based on Monte Carlo simulation, upper 95% confidence interval (top panel), mean (center panel) and lower 95% confidence interval (lower panel).

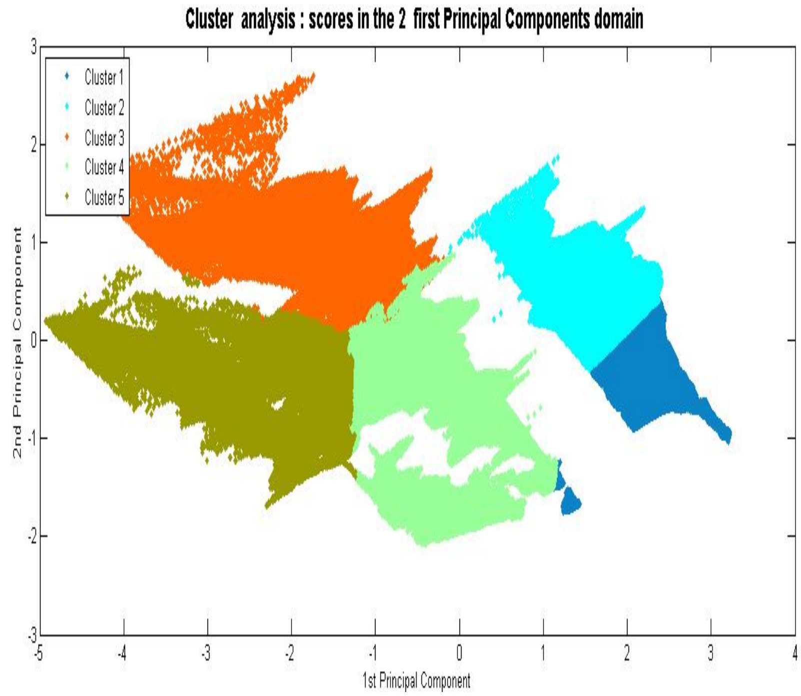

Figure 9 Identification of clusters using the first two principal components for the RI SAMP study area. Cluster definitions, in terms of the input variables, are given in Table 3.

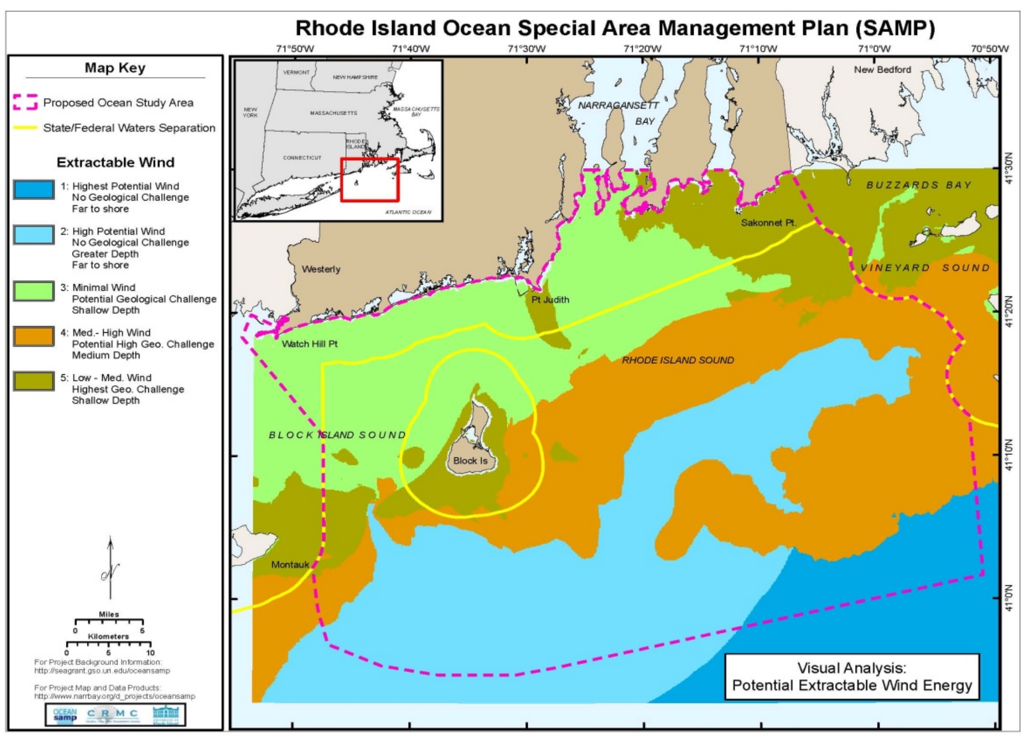

Figure 10 Spatial distribution of the five clusters for the study area. The principal attributes for each cluster are provided in the legend and Table 3.

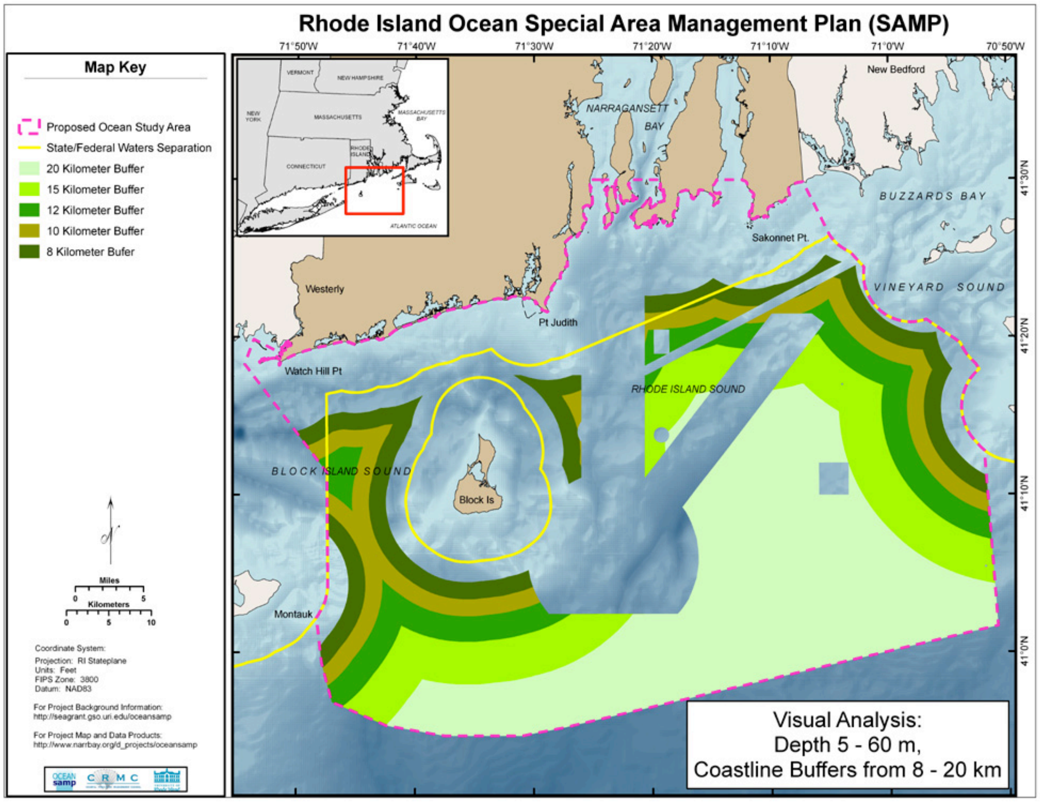

Figure 11 Coastal buffer offsets at 8, 10, 12, 15, and 20 km for the closest land mass.

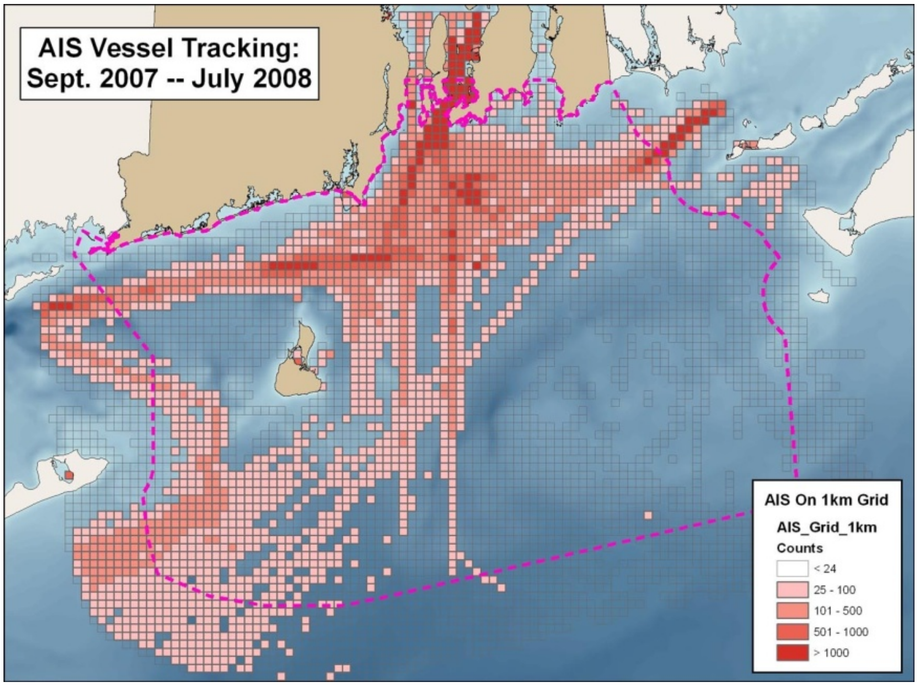

Figure 12 AIS vessel track density data from September 2007 to July 2008 for vessel counts greater than 24.

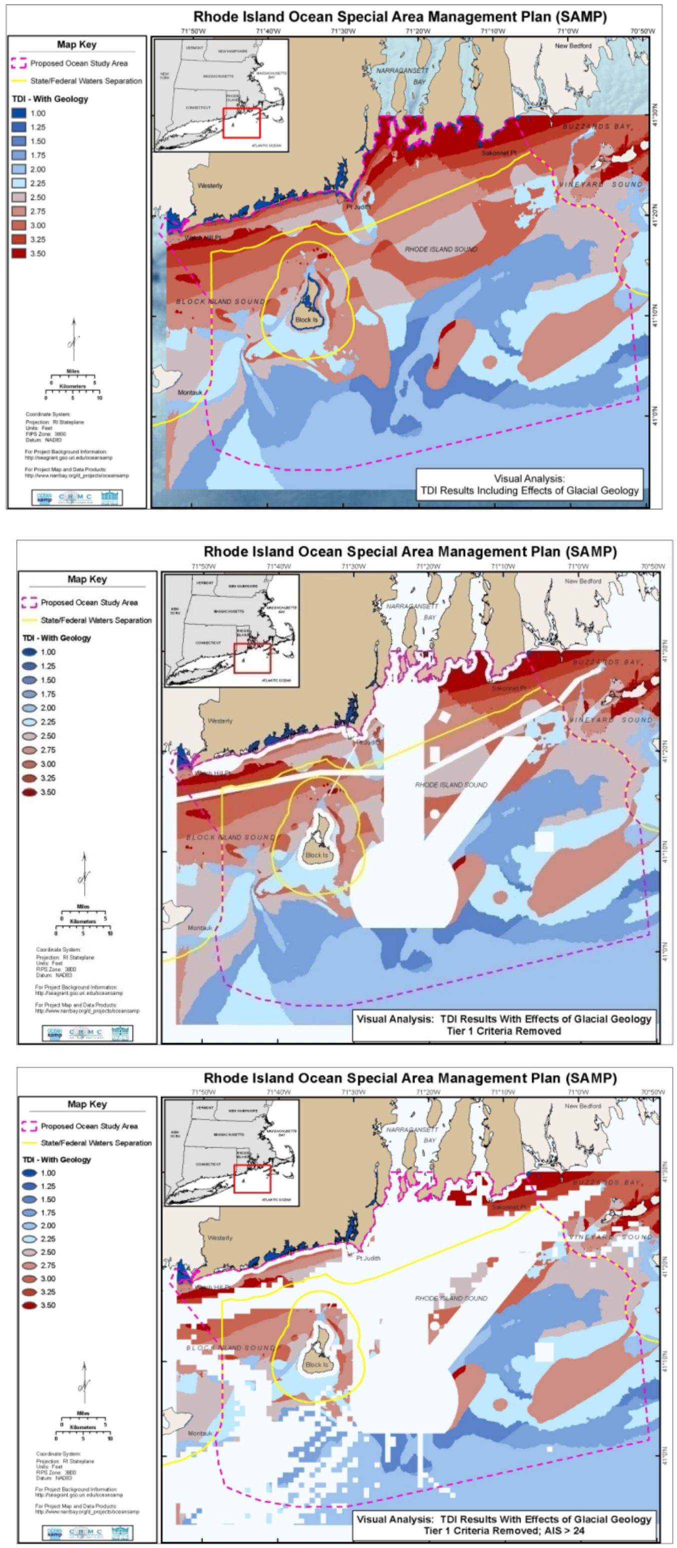

Figure 13 ***TDI*** **(upper panel),** ***TDI*** **with exclusionary areas removed (center panel) and** ***TDI*** **with exclusionary areas and AIS (above 24 counts) removed (lower panel).**

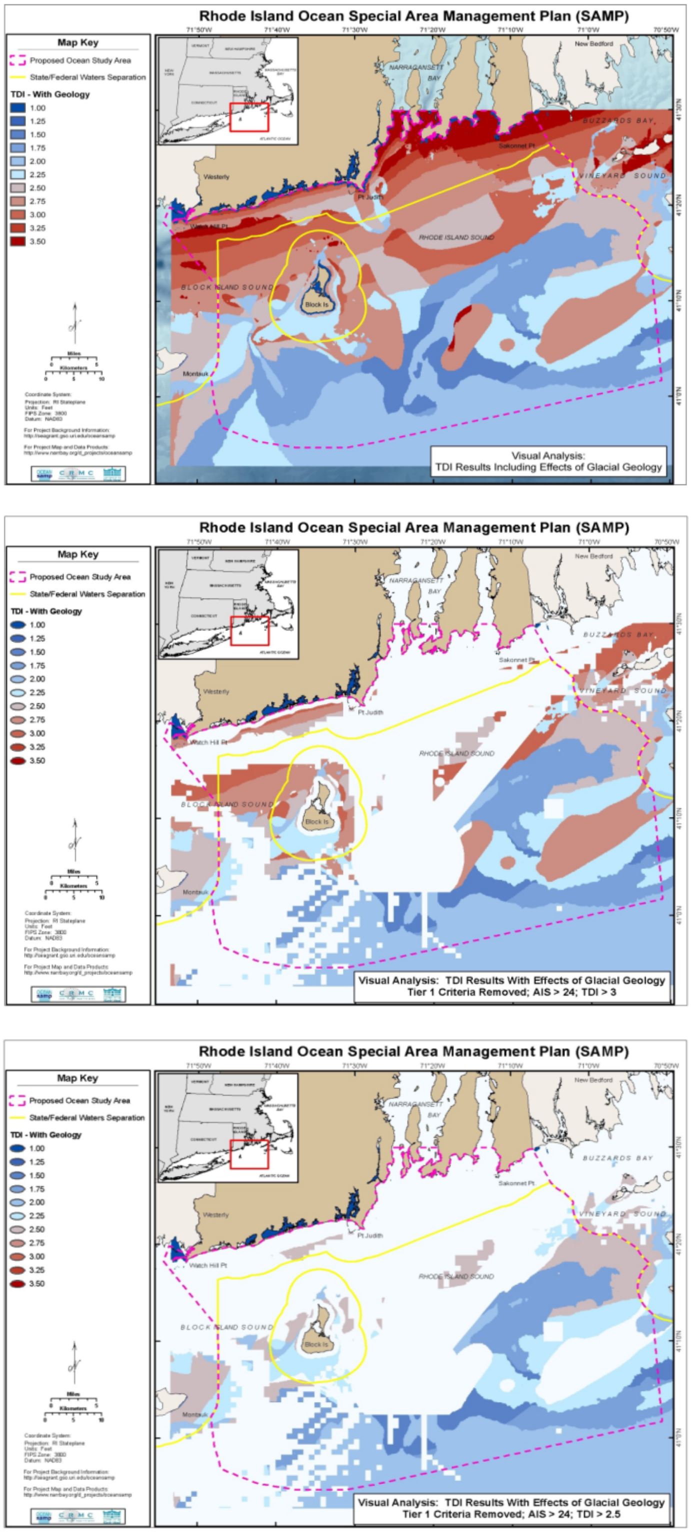

Figure 14 ***TDI*** **(upper panel),** ***TDI*** **greater than 3, AIS greater than 24, and exclusionary areas removed (center panel),** ***TDI*** **greater than 2.5, AIS greater than 24, and exclusionary areas removed (lower panel).**

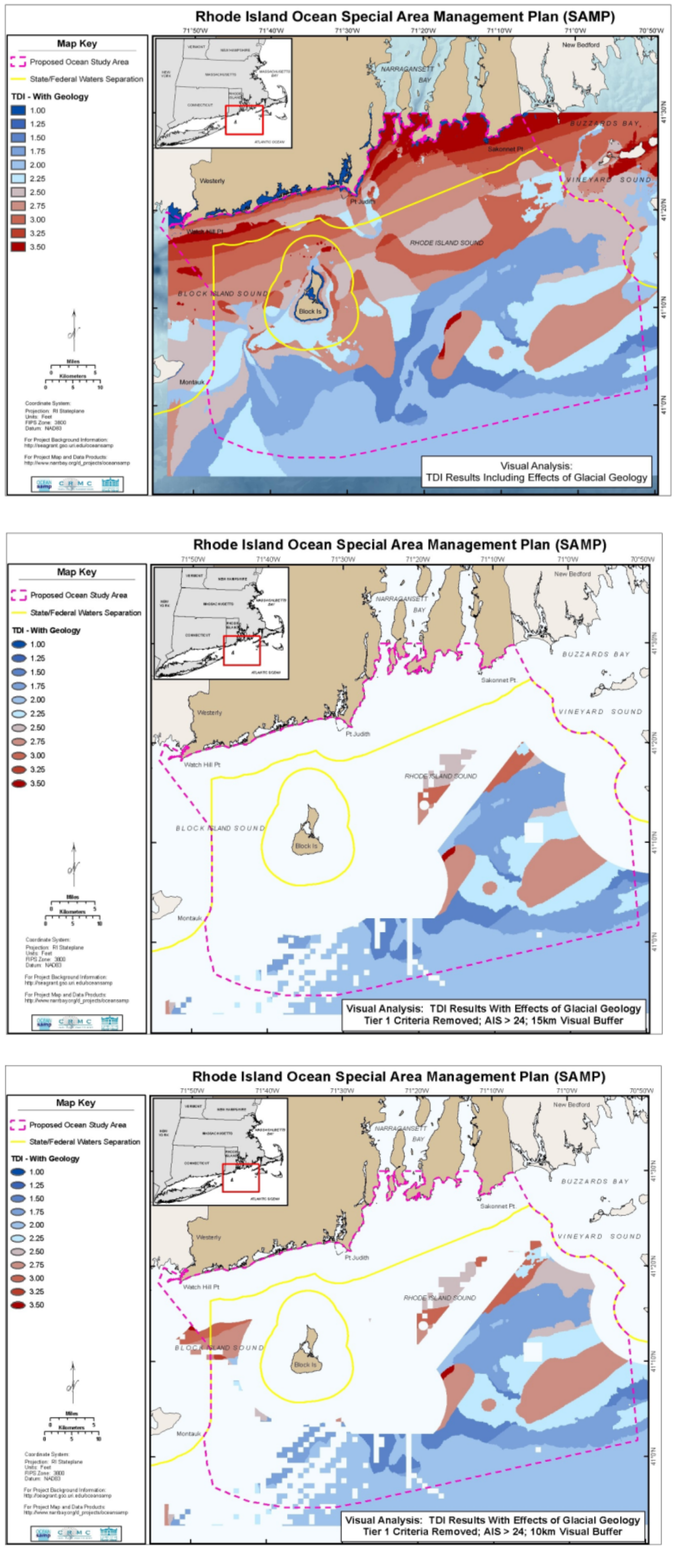

Figure 15 ***TDI*** **(upper panel),** ***TDI*** **with visual buffer 10 km, AIS greater than 24, and exclusionary areas removed (center panel), and** ***TDI*** **with visual buffer 15 km, AIS greater than 24, and exclusionary areas removed (lower panel).**