



# Geological seabed stability model for informing Irish offshore renewable energy opportunities

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**Abstract.** Climate change has driven the European Union to propose a reduction in carbon emissions by increasing renewable energy production. Although Ireland is rich in renewable energy, especially offshore wind resources, it is failing to reduce its annual carbon emissions. This study endeavours to improve Ireland’s marine spatial planning abilities and offshore renewable energy developments by harmonising and customising a unique geological dataset for incorporation into geospatial assessments of Ireland’s continental shelf. A dataset of 1858 points, including 17 new seabed samples collected at strategic sites for this study, is created and used to build a series of geospatial outputs. Data are interpolated with empirical Bayesian kriging to use variogram analyses for probabilistically interpolating coded geological values. The interpolation results are validated through leave-one-out cross-validation and combined with bespoke models of bathymetry and seabed slope using map algebra. The final model reveals areas of relative probable seabed stability based on geological and geomorphological characteristics and is shown to comport with known conditions in several locations. Results suggest that the methods and results presented here could provide useful information to future planning activities and initial site selection assessments.

## 1 Introduction

Anthropogenic climate change is a hazard to human health and society and predictions for its progression depict increasingly dire outcomes without intervention (IPCC, 2014). Research confirms the well-established scientific consensus that carbon emissions must be reduced (Pachauri et al., 2014). Thus informed, the European Union has established ambitious renewable energy goals (EU Renewable Energy Directive (2009/28/EU)) to reduce carbon emissions and mitigate climate change impacts. These goals align with a global trend of increasing renewable energy production (International Energy Agency, 2019).

Positioned downwind of the entire fetch of the Atlantic Ocean, Ireland has abundant offshore wind and wave resources (DCENR, 2014). Unfortunately, it has yet to tap much of this energy and is falling behind other European nations in terms of offshore renewables. Ireland’s carbon emissions are increasing annually by ~2.1 million t despite its goal of reducing these by one million tonnes per year (Climate Change Advisory Council, 2018). Because of these trends, current estimates project Ireland to miss its 2030 EU Effort Sharing Regulation emissions reduction target by 92 million tonnes (ibid). Clearly, additional mitigation efforts are needed, and offshore wind power generation can make a considerable contribution.

Developing offshore wind farms, or any type of energy infrastructure, requires considerable planning and data analysis, which typically include assessments of the energy re-



the most likely sediment characteristics were made manually at these points by relating characteristics from the aforementioned data sources to previously established relationships between seabed morphology, hardness and modelled habitats. Many of these estimates were made outside of the study area to reduce “edging” during subsequent interpolations.

After the data points were compiled into one set, codes were assigned for sediment properties based on available information (lithological descriptions, grain size estimates, and acquisition notes or “deck sheets”). Three attributes were coded: (1) a modified 7-point Folk scale lithology descriptor; (2) a critical bed shear stress ( $\tau_c$ ) value; and (3) an angle of repose. The 7-point Folk scale was chosen as the most consistently reported and standardised metric in the available underlying sedimentary data and was used to guide inferences on the most likely  $\tau_c$  and angle of repose.  $\tau_c$  was adopted as a corollary to general sediment mobility based on long-established hydrological and fluvial principles (e.g. Wiberg and Smith, 1987). While grain size is not the singular factor in  $\tau_c$ , mean sediment size and modality are major contributors to sediment mobilisation (Wilcock, 1993). Furthermore, previous research has revealed reliable relationships between grain-size data and simulated shear stress at smaller scales on the Irish seabed (Ward et al., 2015; Coughlan et al., 2019). Thus, particle size was inferred to be a goal-appropriate corollary to  $\tau_c$  which was adopted as a general sediment mobility predictor. Value estimates for coding  $\tau_c$  were collected from several sources (Table 1). Angle of repose is defined for this study as the steepest angle the seabed sediment is likely to maintain before slope failure from gravity-driven mass wasting and has a well-established correlation with grain size (e.g. Miller and Byrne, 1966); although this attribute is governed by many factors (e.g. grain angularity, sorting and rotation; Miller and Byrne, 1966; Yang et al., 2009), value estimates for coding this sediment property were related to grain size using industrial and academic sources (Table 1). For all attributes, higher numbers were coded for perceived (relative) positive conditions for stability (i.e. higher numbers = higher potential seabed stability). Thereby creating conditions for an “opportunities model,” rather than an “exclusions model.”

### 2.3 Interpolation and validation

Full coverage rasters of the geological data were created at 500 m<sup>2</sup> resolution through geostatistical interpolation by Empirical Bayesian Kriging (EBK) using ESRI’s ArcGIS software version 10.6 following data screening to determine if the data needed to be transformed before it was kriged (Oliver and Webster, 2014). Kriging was used because it is a probabilistic, not deterministic, geostatistical interpolation method that enables cross-validation of the results (Aelion et al., 2009). EBK was specifically chosen to incorporate variographic assessments that enable subgroups of points to be interpolated independently from overall data trends (see Ae-

lion et al., 2009; Oliver and Webster, 2014; Samsonova et al., 2017). 100 variogram models were simulated for each subset of points (100 points per subset) for all interpolations in this study.

Model validity and the appropriateness of the interpolated data were assessed using leave-one-out cross validation, which kriges the data while sequentially removing each individual datum to validate local model results. Validation outputs were assessed as the Root Mean Square Error (RMSE) and Root Mean Square Standardized Error (RMSSE) which are shown in Eqs. (1) and (2), respectively (Gaida et al., 2019).

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (\hat{Z}(x_i) - z(x_i))^2}{n}}, \quad (1)$$

Where  $n$  is the number of samples;  $\hat{Z}$  is the value that has been predicted (at location  $x_i$ ) and  $z$  is the measured value that has been omitted at the same location.

$$\text{RMSSE} = \sqrt{\frac{\sum_{i=1}^n [(\hat{Z}(s_i) - z(s_i))/\sigma(s_i)]^2}{n}} \quad (2)$$

Where  $\sigma(s_i)$  is the standard error of the prediction at site  $s_i$ .

### 2.4 Geomorphology calculations and seabed modelling

EMODnet bathymetric data were resampled to 500 m<sup>2</sup> resolution (from  $\sim 100$  m<sup>2</sup>) and rescaled exponentially in ArcGIS to simplify the deep-water (approximately > 60 m depth) seabed and emphasise the importance of shallow depths by consolidating high values there. This was done to model the increasing probability of strong currents and wave action in shallow ocean conditions. Because ocean shallowness typically correlates positively with distance to shore (i.e. depth typically increases with distance from shore), this also provides a secondary emphasis on seabed mobility from terrestrial sediment input and anthropogenic perturbations, which logically tend to converge towards shore.

Seabed slope was calculated using the geomorphometry tool package: Benthic Terrain Modeler (Walbridge et al., 2018), which computes local seabed angles using a floating neighbourhood assigned as a three-pixel by three-pixel area (Walbridge et al., 2018). The relative importance of steep slopes to seabed mobility was weighted by exponentially rescaling the slope calculations to a new raster in ArcGIS, similar to the bathymetric modelling described above.

The probability of seabed stability was modelled by summing the  $\tau_c$ , angle of repose, modified bathymetry, and slope angles. The aforementioned rescaling functions applied to each of these rasters ensures that they cover the same range of values (1–100). Assigning identical scales to each dataset helped assure that no single aspect was spuriously weighted as more or less important to the others.

**Table 1.** Coded sediment properties.

Factor	Sediment type (Folk-7 code)	Mean reported value <sup>a</sup>	Coded value <sup>b</sup>	References
Critical bed shear stress ( $\tau_c$ ) ( $\text{Nm}^{-2}$ )	mud (1)	0.06	1	Wiberg and Smith (1987); USGS (2008)
	sandy mud (2)	0.09	1	
	muddy sand (3)	0.15	2	
	sand (4)	0.22	3	
	mixed sediment (5)	4.01	4	
	coarse sediment (6)	22.62	5	
	rock and boulders (7)	125.20	5	
Angle of repose ( $^\circ$ )	mud (1)	17.00	1	Miller and Byrne (1966); Yang et al. (2009); Froehlich (2011); Al-Hashemi and Al-Amoudi (2018)
	sandy mud (2)	17.50	1	
	muddy sand (3)	17.50	1	
	sand (4)	21.75	1	
	mixed sediment (5)	40.00	3	
	coarse sediment (6)	36.52	3	
	rock and boulders (7)	NA <sup>c</sup>	5	

<sup>a</sup> Calculated from values compiled from the reviewed literature cited in the “Reference” column.

<sup>b</sup> Coded for interpolation in a GIS. Values were adjusted to higher numbers if the sediment was reported as consolidated or “stiff,” especially for mud facies.

<sup>c</sup> No reference for rock or boulders was found for angle of repose; a large value was assumed because rock outcrops can maintain stability at extremely steep angles depending on composition and structure and logic dictates that lithified grains can maintain steeper angles than loose ones.

### 3 Results

#### 3.1 Data collection

The sedimentary data collection efforts for this research provided 1858 data points (Supplement); sources are summarised in Table 2 and all data points are shown in Fig. 1. Most data were sourced from the Marine Institute and these were typically sediment samples collected within  $\sim 12$  nm from shore (Table 2). Samples without descriptions adequate for identifying a sediment type and Folk-7 grain size were removed. Sixty-four data points were collected from 13 journal articles that were used to reduce data gaps. Additional data gaps were filled using the estimated datapoints at 25 km spacing, which resulted in 278 more data (Fig. 1; Table 2).

#### 3.2 Interpolation

The point data were assessed for appropriateness for kriging via visual inspections of geostatistical histograms, which showed that the data were found to be distributed relatively normally with standard deviations of  $\sim 1.3$ , and skewness of  $-0.2$ . Thus, no transformations were performed to reduce potential outlier effects to the interpolations and the “Power” variogram model was used to balance computational requirements and accuracy (ESRI, 2016).

This gaussian distribution also suggests that the RMSE is an appropriate method for validating of the model (Chai and Draxler, 2014). The leave-one-out cross-validation showed the EBK interpolations to be highly valid. RMSE values were all very close to zero (Table 3), indicating that interpolated values were often consistent with actual values (Ar-

slan, 2012). Furthermore, values for the RMSSE were typically close to one, indicating validity, and most often less than one, suggesting that predictions may overestimate variability (Gaida et al., 2019). This potential overestimation is not necessarily a drawback, given the simplified characterisations of the sedimentary data required to code information for use in the model.

Results from the Folk-7 sediment categories are interpolated (Lark et al., 2012) and presented here (Fig. 2) despite these values not being directly used in the following seabed stability model. These interpolated values and the resulting map provide a stand-alone output that adds to previous seabed mapping efforts for Ireland (e.g. EMODnet Geology Consortium, 2019). The area covered by each interpolated sediment type is calculated in a GIS and shown in Table 4. Sand is revealed to be the most common seabed sediment (Fig. 2), covering  $\sim 63\,400$  km<sup>2</sup> of the study area ( $\sim 48\%$ ; Table 4). Rock and muddy sediments are shown to be rare on the shallow ( $< 200$  m depth) Irish continental shelf (Table 4) and mud is mainly found in the Irish Sea “mud belt” (Belderson, 1964; Coughlan et al., 2015). Some outcrops of sub-glacial diamiction are discernible in the interpolated raster, at least in western Ireland, where bands of mixed sediment (ostensibly from sampled diamictic facies) can be identified roughly aligning with mapped moraines and grounding-zone wedges associated with the last British-Irish Ice Sheet (Peters et al., 2015, 2016; Fig. 2).

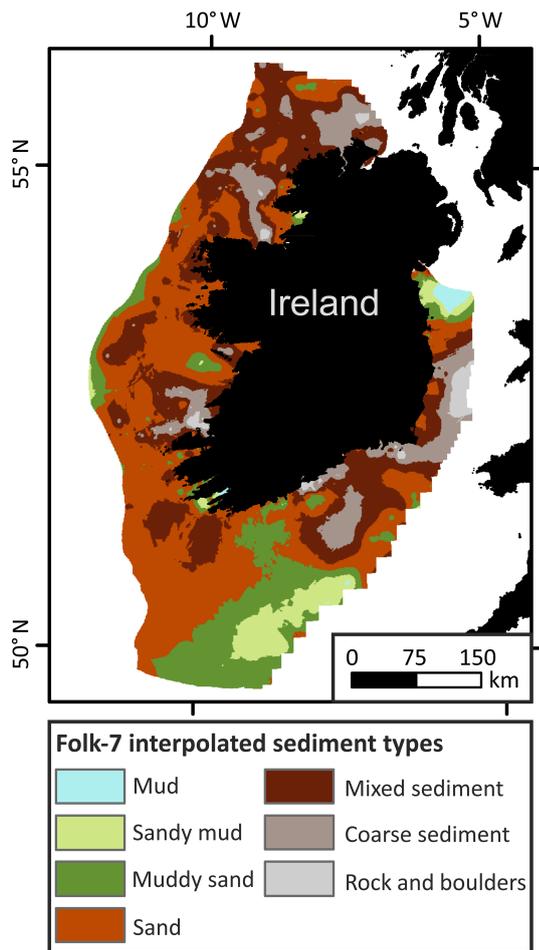
Results of the EBK interpolations and raster rescaling are shown in Fig. 3. The mapped outputs of these results reveal similar data distributions for  $\tau_c$  and angle of repose; however high values for angle of repose are less extensive. This is ex-

**Table 2.** Summary of data collection and estimation work.

Source (type)	Number of data points	Type of data points	Primary location
INFOMAR (public)	1495	Various sediment grabs and vibrocores	Everywhere, but most common within ~ 12 nm of shore
British Geological Survey (2020) (public)	4	Sediment grabs	Celtic Sea (south of Ireland)
This study (new data)	17	Shipek sediment grabs and vibrocores	Near ports that may be suitable for supporting offshore developments
Huvenne et al. (2002) (journal article)	3	Sediment cores	Porcupine Seabight (south west of Ireland)
Van Rooij et al. (2003) (journal article)	1	Sediment core	Porcupine slope (south west of Ireland)
Raes and Vanreusel (2006) (journal article)	1	Box core	Porcupine Seabight (south west of Ireland)
Heindel et al. (2010) (journal article)	1	Image	Porcupine Seabight (south west of Ireland)
Peters et al. (2015) (journal article)	4	Vibrocores	Porcupine Bank (west of Ireland)
Peters et al. (2016) (journal article)	13	Vibrocores	West of Ireland
Delivet et al. (2016) (journal article)	1	Core	Goban Spur (south west of Ireland)
Lim et al. (2017) (journal article)	1	Image	Porcupine Seabight (south west of Ireland)
Callard et al. (2018) (journal article)	2	Vibrocores	North west of Ireland
Lockhart et al. (2018) (journal article)	19	Sediment cores	Celtic Sea (south west of Ireland)
Scourse et al. (2019) (journal article)	8	Sediment cores	Celtic Sea (south of Ireland)
Somerfield et al. (2019) (journal article)	1	Box core	Celtic Sea (south of Ireland)
Callard et al. (2020) (journal article)	9	Vibrocores	West of Ireland
This study (estimates)	278	Seabed estimates from backscatter, bathymetry and EMODnet models	Everywhere, but most common in the Celtic Sea and outside the study area

**Table 3.** Mean results for all points for the leave-one-out cross-validation of the EBK interpolations used in the seabed stability model.

Analysis	RMSE	RMSSE
EBK shear	0.001511	0.859344
EBK shear (without 278 estimated points)	0.005825	0.829315
EBK angle of repose	0.015312	0.91401
EBK angle of repose (without 278 estimated points)	0.015357	0.919219

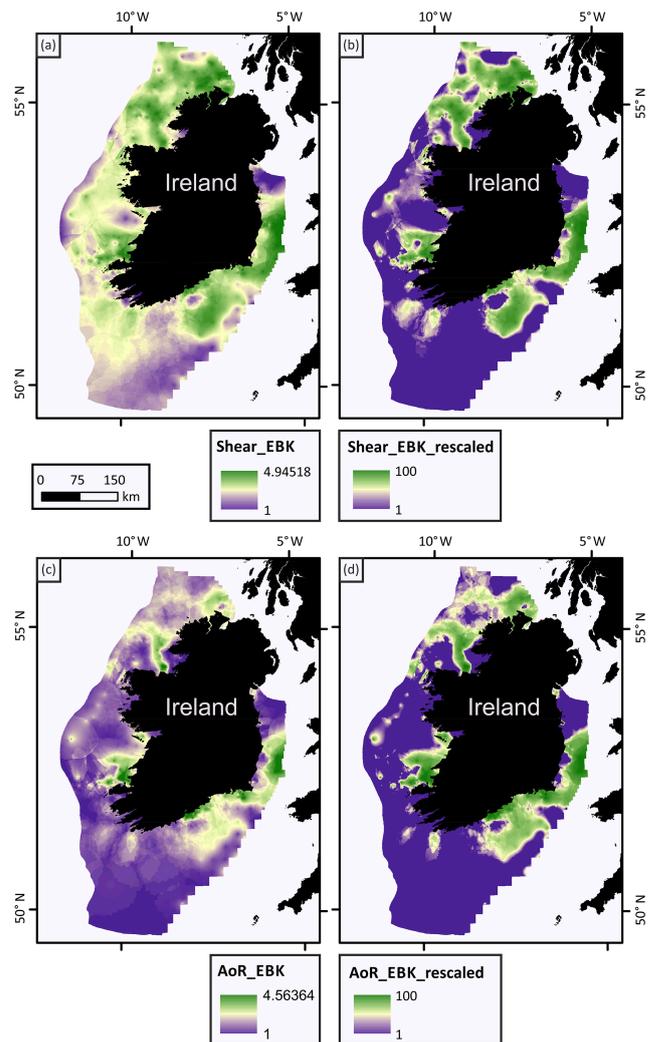


**Figure 2.** Map of interpolated values of the coded Folk-7 sediment categories (coded values in Table 1).

**Table 4.** Area covered by each interpolated Folk-7 sediment type (as calculated in a GIS).

Folk-7 sediment type	Total area (km <sup>2</sup> )	% of study area
Mud	588.897	0.45
Sandy mud	5465.898	4.15
Muddy sand	22 857.377	17.36
Sand	63 396.822	48.14
Mixed sediment	32 960.742	25.03
Coarse sediment	6259.438	4.75
Rock & boulders	178.221	0.14

pected from the differences in value coding (Table 1). Clear similarities in the patterns of likely sediment stability can be seen after the initial results are rescaled (Fig. 3b, d); this was also expected given the common origin of the coded sediment properties (the sedimentary dataset shown in Fig. 1).



**Figure 3.** Sediment property interpolation and rescaling results. (a) EBK interpolation results for critical bed shear stress. (b) Rescaling results for the critical bed shear stress raster. (c) EBK interpolation results for angle of repose. (d) Rescaling results for the angle of repose raster.

### 3.3 Seabed stability modelling

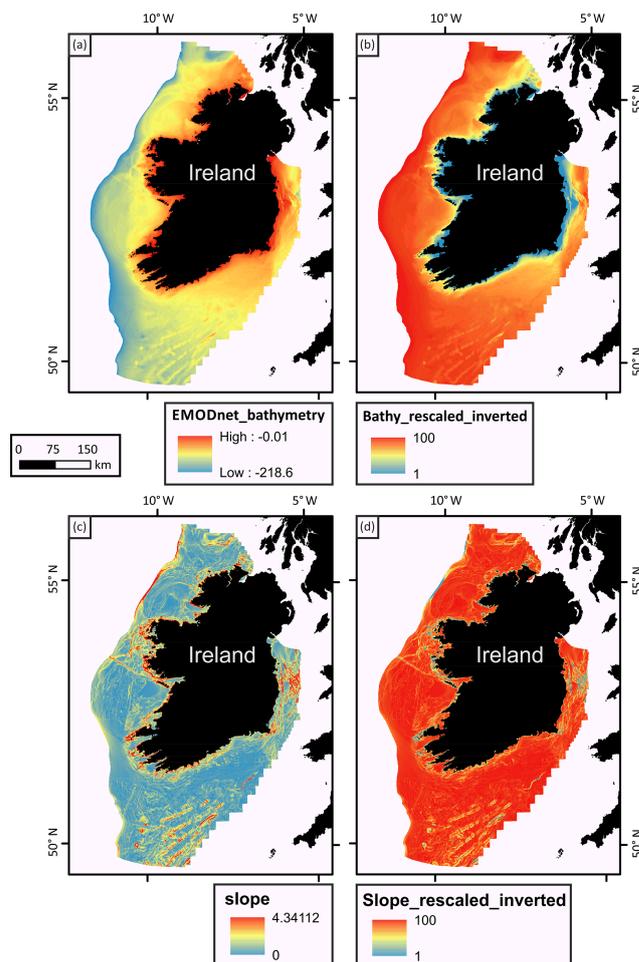
The results of the initial seabed modelling for bathymetry and slope are shown in Fig. 4. The modified bathymetric model (data were rescaled exponentially and inverted) reveals a relatively wide band of shallow water in the Irish Sea (east of Ireland) which contributes to near-shore seabed instability potential (Fig. 4b). Conversely, the Atlantic Ocean off western Ireland is characterised by deeper water, but nearshore instability is more likely from steeper seabed slopes (Fig. 4d). Megaridges in the Celtic Sea (Lockhard et al., 2018) create a series of small, steep slopes (Fig. 4c, d). However, these slopes typically do not result in as many low values (i.e. high slope angles) as the near-shore data from the bathymetric model (Fig. 4b).

These preliminary outputs (Fig. 4) are summed together with the interpolated sedimentary seabed models (Fig. 3) to estimate the overall seabed stability (Fig. 5). In this final model output, higher (unitless) values generally correspond to seabed conditions typified by coarse and/or consolidated material at low slopes and in relatively deep water. A large area of rocky and coarse-grained seabed with shallow slopes in the Celtic Sea, south of Ireland, is identified as relatively immobile. Areas interpolated from rock or boulder Folk-7 geological data, which are most often found within 12-nm of shore, are also identified as stable. This reflects the scope of this model (to predict areas of stable seabed) and highlights the need for careful interpretation in its use – predicted instability is not necessarily synonymous with unsuitable for development.

Several locations of fine-grained seabed sediments proximal to shore are identified as the most geologically unstable areas. All other variables being equal (e.g. METOcean conditions, sediment influx rates, ocean currents), these areas are modelled to be most likely to experience seabed mobilisations and will likely require the greatest mitigation efforts (e.g. environmental monitoring, scour protection, dredging) if they are developed. Several lines of evidence corroborate these results. Firstly, sediment mobilisation and subsequent removal of muddy sediments in the Irish Sea has been shown to occur relatively quickly and to be exacerbated by anthropogenic activities (Coughlan et al., 2015). And secondly, dredging reports from Ireland's first (and currently only) offshore wind farm, Arklow Bank (Fig. 5), document sediment accumulation at rates that may compromise safe access to the turbines without removal (Moore et al., 2016). This suggests that sediment mobilisation was significant following installation of turbine foundations, which aligns with documented evidence (Whitehouse et al., 2011). The potential mobilisation of both the Irish Sea mud belt and sandy sediments near Arklow Bank are predicted by the final seabed stability model (Fig. 5).

#### 4 Model limitations and future work

This model is a promising addition to ongoing research seeking to inform Irish marine spatial planning and site investigations for potential offshore renewable energy developments. Additionally, this work documents a promising method for collecting and interpolating various types of geological data. However, this model has been designed to be used in GIS-based multi-criteria decision analyses with other parameters to help provide more complete assessments. Furthermore, the work presented here was informed solely by bathymetry and the composition of the seabed, which are not the only factors driving sediment mobility. Thus, for example, this model cannot distinguish areas of seabed stability due to inherently stable sediments, from areas undergoing modern winnowing and active fine particle mobilisation due to local cur-

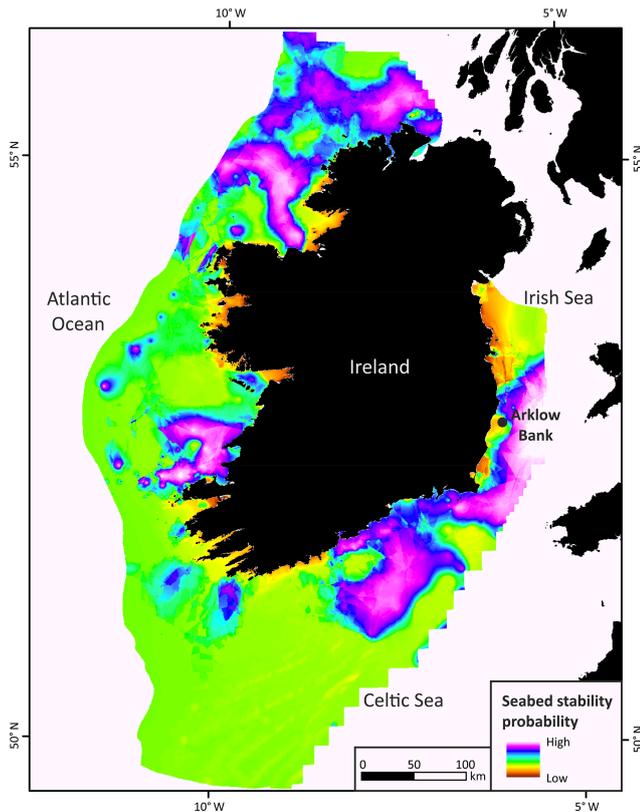


**Figure 4.** Bathymetry and slope modelling, rescaling, and inversion results. (a) Original EMODnet bathymetric data. (b) Rescaled and inverted bathymetric data, modelled to estimate the influence of depth and distance from shore on sediment stability. (c) Slope calculation results. (d) Rescaled and inverted slope raster.

rents – which would likely lead to unstable seabed conditions following disruptions from infrastructure installation. Future work should build on this research by incorporating modelled metocean forcing data that will enable an assessment of a primary erosive mechanism that drives sediment mobilisation.

#### 5 Conclusions

This new model of seabed stability is unique from previous efforts because it is guided by engineering aspects of offshore development for renewable energy infrastructure. Thus, sedimentary properties are used to relate the likely seabed conditions to the most pertinent aspects of sediment mobility for the installation and maintenance of foundations for renewable energy structures. These characteristics are also important for assessing the potential for environmental disturbances following foundation installations. Given the am-



**Figure 5.** Raster output from the final seabed sediment stability model combining coded sediment properties, bathymetry, and slope. The location of Ireland's only offshore wind farm, Arklow Bank, is shown as a labelled black dot.

bitious goals established by the Climate Change Advisory Council (2018) to curb Ireland's carbon emissions, this geological aid to de-risking marine development is highly relevant. No other bespoke geological tool was previously available at such a scale.

The new model presented here harmonises various seabed data ( $N = 1858$ , ranging from samples to photographs) to create a bespoke dataset for assessing the Irish continental shelf for offshore renewable energy development. The compiled data are interpolated via empirical Bayesian kriging, a well-established geostatistical technique typically used in geological and environmental analyses. The interpolation results extend data coverage while rendering the dataset compatible with common geospatial assessments used in offshore site selection investigations and marine spatial planning efforts. Highlights include:

- A novel dataset composed of 1858 data of various types, including 17 new seabed samples strategically collected for this study, is harmonised and coded for unique, regional geostatistical analyses and geospatial interpolation.

- A new rasterised, continuous seabed map is provided that is shown to comport spatially with several known sediment types and Quaternary seabed processes. This output helps qualitatively validate the seabed stability models derived from much of the same data and provides new seabed data that may aid in future habitat mapping or planning assessments.
- Empirical Bayesian kriging is shown to be a useful addition to geospatial assessments of offshore renewable energy potential and the results of the interpolations used for this study are shown to be mathematically valid through leave-one-out cross-validation.
- Interpolated sediment properties reveal patterns in the probabilistic distribution of seabed stability derived from the original sedimentary dataset.
- Models of seabed slope and bathymetry that are customised for highlighting geomorphically stable areas are presented. These models weight high angles and shallow depths exponentially to reflect the importance of these aspects in seabed stability.
- The models of sediment properties, angle and bathymetry are summed together in a GIS to model the overall probability of seabed stability for the shallow (< 200 m deep) Irish continental shelf. This map is shown to accurately highlight relative seabed instabilities in several locations and can be used in future multi-criteria decision analyses in GIS environments. This is a promising result for establishing regional or national-scale geological models that are useful for preliminary offshore renewable energy planning.

*Data availability.* Sources for existing publicly available data are provided; information on new data presented in this study is provided in the Supplement.

*Supplement.* The supplement related to this article is available online at: <https://doi.org/10.5194/adgeo-54-55-2020-supplement>.

*Author contributions.* JLP performed the conceptualisation, data curation, formal analysis, validation, visualisation, and writing. FB assisted in GIS analysis and writing. RO'C aided in conceptualisation and visualisation; AW aided in conceptualisation and provided supervision. AJW, VC, and JM acquired funding.

*Competing interests.* The authors declare that they have no conflict of interest.

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