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Geological and geotechnical constraints in the Irish Sea for offshore renewable energy

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ABSTRACT

A 1:1,000,000 map of the Irish Sea, within the Irish Economic Exclusion Zone, is presented highlighting the spatial distribution of potential geological and geotechnical constraints to offshore wind energy development. In this mapping exercise we incorporated existing multibeam echosounder bathymetric and backscatter data collected by the Integrated Mapping for the Sustainable Development of Ireland’s Marine Resource programme. ArcGIS was used to interrogate the bathymetric data and produce maps for seabed morphological characteristics. Backscatter data and QTC Multiview derived sediment classification was used in conjunction with data from the literature to link sediment distribution with sediment transport pathways and to assess the possible impact on infrastructure. The result is a spatial constraints map, which may be used by developers, consultants and marine spatial planning authorities alike to help site projects and plan de-risking site investigations.

1. Introduction

With an energetic wind regime and relatively shallow water depths, the Irish Economic Exclusion Zone (EEZ) within the Irish Sea and its approaches are considered suitable for the economical development of offshore wind generation. The Irish EEZ of the Irish Sea has been technically recognised as being able to support up to 4.8 gigawatts (GW) of fixed offshore wind ‘without any likely significant adverse effects on the environment’ (Department of Communications Energy and Natural Resources [DCENR], 2014). More recently, under Action 25 of its Climate Action Plan 2019, the Irish Government has set a target of 3.5 GW of electricity from offshore wind sources by 2030 (Department of Communications Climate Action and Environment [DCCAE], 2019). Moreover, Under Action 26 of the Plan, the Irish Government has promised to support emerging marine technologies, including exploring for test locations (DCCAE, 2019). In this context, however, to date only one offshore windfarm has been developed in the Irish sector of the Irish Sea; Arklow Bank, a 25 megawatt (MW) project constructed in 2004 on a sand bank. Correspondingly, almost 2.7 GW of offshore wind has been successfully installed in the UK sector of the Irish Sea. However, a number of offshore wind projects in the UK sector have encountered adverse geological conditions which have resulted in their discontinuation (e.g. Celtic Array: Mellet et al., 2015). Therefore, as Ireland looks to further develop its offshore wind capacity, understanding the seabed sediments and sub-surface structure regarding siting of offshore wind energy devices is part of the first stage assessment towards a sustainable, national marine energy development strategy.

Water depth and seabed geology are key considerations for the feasibility of offshore wind installations (Barrie & Conway, 2014; Bosch et al., 2018; Cavazzi & Dutton, 2016; Cradden et al., 2016; Le et al., 2014). Since 2003, the Integrated Mapping for the Sustainable Development of Ireland’s Marine Resource (INFOMAR) programme, a joint venture between the Geological Survey of Ireland (GSI) and The Irish Marine Institute (MI), has been collecting a variety of geophysical and groundtruthing data in the Irish Sea. This high-resolution and spatially extensive dataset allows for a regional assessment of seabed conditions pertinent to offshore renewable energy development.

The objective of this study is to spatially map the key seabed characteristics and sedimentary processes affecting potential offshore wind deployment in the Irish EEZ of the Irish Sea. To do so, we utilise the existing, high-quality geological and geophysical dataset gathered by the INFOMAR programme and apply detailed analysis to spatially constrain the geological and geotechnical constraints that need to be considered.
as part of any future site evaluation for offshore renewable energy development.

2. Materials and methods

Approximately 8200 km² of multibeam echosounder (MBES) data used in this study were acquired during 36 separate surveys in the Irish Sea and its approaches from 2003 to 2014 (Figure 1; Inset, Main Map). The Kongsberg Simrad 3002D system was predominately used. The Simrad 3002D system allowed the acquisition of bathymetric and backscatter data in the 300 kHz range using dynamically focused beams. The horizontal accuracy (x, y) was usually <50 cm with a vertical accuracy (z) of <15 cm obtained for the processed bathymetry data. The Simrad EM1002 system was also used for multibeam echosounder data acquisition, operating at frequencies between 93 and 95 kHz. Data processing was typically performed on board with the CARIS HIPS and SIPS software package to remove erroneous pings and correcting for tides. Data were accessed and downloaded through the INFOMAR Interactive Web Data Delivery System (IWDDS).

Figure 1. Extent of INFOMAR MBES bathymetry data used in this study (A) and same data gradated to 0–40 m (shallow), 40–60 m (transitional) and >60 (deep) representing preferred ranges for technology types (B).
Whilst the bathymetric datasets derived from MBES are easily managed and merged to form a coherent dataset, the inherent differences in collection between backscatter datasets (e.g., different vessels, different MBES equipment, different MBES settings) meant that generating coherent backscatter reflectivity (db) value levels is difficult (F. Sachetti, pers. Comm.). Similarly, given the large area involved in this study, it was unrealistic to use individual data grids in any meaningful way. However, it is possible to apply static db value shifts to backscatter layers in order to match one another and thus help standardise them, making the various surveys as similar as possible and produce a dataset that is usable. The Marine Institute have done this using Geocoder software and the resulting dataset was requested from them and used in this study. Backscatter and sediment classification data were accessed and downloaded through the INFOMAR Web Map Service (WMS) using the ArcGIS REST Services Directory.

### 2.1. Multibeam echosounder data

A total of 36 raster tiles were used to build a MBES bathymetry mosaic. Given that data were collected by different vessels and multibeam echosounder acquisition systems and gridded to different resolutions, data needed to be at a common resolution (cell size) before it could be combined. Therefore, raster tiles were re-sampled to a 5 m cell size using the ‘Resample Tool’ in the ArcGIS Data Management Toolbox. Once all raster tiles had been re-sampled, they could then be combined into a single, seamless file using the ‘Mosaic to New Raster’ tool in the ArcGIS Data Management Toolbox (Figure 1(A)). A gridded dataset was also generated to assess areas for suitable foundations with respect to wind turbine installations based on water depth categories from Bosch et al. (2018) (Figure 1(B)). Water depths of 0–40 m were considered ‘shallow’ and suitable for monopile, mono-bucket (suction bucket) and multi-pile (tripod and jacket). Depths of 40–60 m were classified as ‘transitional’ and preferential for multi-pile and gravity base structures (GBS). Water depths greater than 60 m were considered ‘deep’ and likely to be more suited to floating technologies.

### 2.2. Bathymetric derivatives

The bathymetry mosaic grid was used to generate several additional parameters and gridded datasets. Using IVS Fledermaus rugosity was derived to measure surface roughness and terrain variability (Figure 2). Within ArcGIS a slope angle dataset was derived using the Spatial Analyst Tools. Slope data were used to and assess where areas may exceed critical thresholds for certain foundation types, such as gravity bases. In this study greater than 5° was considered a significant seabed gradient (Gavin and Doherty Geo-Solutions, 2012; Figure 2).

The Benthic Terrain Modeler (BTM) is a plug-in extension for ArcGIS that be used to calculate fine- and broad-scale Bathymetric Position Indices (BPI) (Walbridge et al., 2018). BPI can be used to define the elevation of a particular location relative to the overall grid area. Therefore, it is a useful tool in defining positive topographic features like banks, as well as negative topographic features (e.g. troughs and channels). In this study, the broad-scale BPI was calculated with an inner search radius of 25 m and an outer search radius of 250 m giving a scaling factor of 1000 (Figure 3). The fine-scale BPI was calculated using an inner search radius of 3 m and an outer search radius of 25 m to give a scaling factor of 100 (Figure 3). These datasets were then standardised to allow for easier comparison of outputs.

### 2.3. Backscatter and sediment classification

Backscatter was used in conjunction with bathymetry data and automated sediment classification to map sediment distribution based on acoustic response, seabed morphology and sediment samples. With backscatter data, the intensity of the return signal can be indicative of a soft (low response and, therefore, a light colour) or a hard (high return, dark colour) substrate (Figure 4). It can be used to infer sediment type and distribution between sample points.

Acoustic classes corresponding to different sediment types were extracted from the backscatter data using various methods: image segmentation, isoclustering and manual tracings. Acoustic classes were classified into seabed substrate types using sediment sample data. A modified classification scheme was used for the sediment classification based on Folk (1954) (Figure 4).

### 3. Results and discussion

#### 3.1. Seabed Morphology

The BPI for the Irish Sea proved useful in defining areas of flatness, elevation and depression (Figure 3). These areas could then be classified as morphological features according to the classification system of Dove et al. (2016). Areas of flatness are generally found in the northern part of the Irish Sea and correspond with the end of the dominant transport pathways where fine sediment is deposited (Figures 4, 5 and 8). Contrasting areas of elevation and depression are found in the southern part of the Irish Sea, and its approaches, where there are positive features, such as banks and rock outcrops, as well as negative features including scour pits and channels (or tunnel valleys). The crests and troughs of individual sediment waves
form positive and negative features respectively. This proved useful in mapping geomorphic features which may act as constraining factors for offshore wind energy deployment due to sediment migration or adverse ground conditions (Figures 5 and 8). Offshore wind farms are often sited on stable sand banks where water depth is shallow.

3.2. Sediment distribution and processes

Where bed-stresses at or near the seafloor interact with unconsolidated sediments they can be mobilised when critical sediment thresholds, controlled primarily by sediment grain-size, are exceeded. These bed-stresses are driven by a combination of water depth and the hydrographic regime. In the Irish Sea the hydrographic regime is controlled by tidal energy, along with seasonal stratification of the water column and strong winds. Tides enter the Irish Sea from the North Channel and St. Georges Channel to the south and where they meet a degenerate amphidrome is formed in the south Irish Sea, off Wicklow. Tidal ranges increase in opposite directions, north and south, from this point and bedload parting zones have been observed where there are divergent patterns in sediment transport direction (Holmes & Tappin, 2005; Pingree & Griffiths, 2005).
The magnitude of migration tends to dissipate away from these bedload zones with the highest bedform migrations rates (up to \(35 \text{ m/a}^{-1}\) on average), recorded in the central part of the Irish Sea in an area dominated by coarse-lag deposits and sediment wave fields (Van Landeghem et al., 2012, 2009; Ward et al., 2015) (Figure 6). These areas correspond with areas of high rugosity (Figure 2). There are well established pathways that transport sediment northward where it is deposited in an area of low bed-stress, forming a large sediment patch of sandy Mud to Sand grade material (Figure 6). This area of fine sediment accumulation forms a relatively flat area of elevation referred to as the Western Irish Sea Mud Belt (WISMB) (Belderson, 1964; Holmes & Tappin, 2005; Jackson et al., 1995; Ward et al., 2015) (Figure 5). As a result, Irish Sea sediments consists of a mosaic of reworked glacial and post-glacial sediments which form a range of grain-size classes (Dobson et al., 1971; Jackson et al., 1995; Ward et al., 2015).

3.3. Geological and geotechnical constraints

The shallow geology of the seabed can offer significant constraining factors to the installation and subsequent
stability of offshore infrastructure, like wind turbine foundations (Cotterill et al., 2017; Mellet et al., 2015). In addition, active seabed processes can adversely impact these structures, such as the removal of sediment from around foundations causing instability (i.e. scour). To determine the primary constraints, and so inform mapping, a comprehensive review of literature related to Irish Sea Quaternary geology and industry best-practice related to siting offshore infrastructure was undertaken. Subsequently, a summary checklist of geological characteristics, processes and their potential constraining properties was adopted from Mellet et al. (2015) (Table 1).

Previously, as part of the Offshore Renewable Energy Development Plan (DCENR, 2014), the Irish Sea and its approaches was classified into three assessment areas: East Coast (North), East Coast (South) and South Coast. Each one was technically assessed for its potential to support offshore wind development in terms of gigawatts (GW) that could be deployed. Using Table 1, geological and geotechnical constraint areas in the Irish Sea were delineated, digitised and overlain with the OREDP assessment zones to indicate the main engineering and siting challenges in each zone (Figure 7 and Main Map).

Figure 4. Backscatter (A) and sediment classification (B) data available from INFOMAR used in this study.
3.3.1. Soft sediments

Soft sediments are predominately found in the area in the north Irish Sea within the Western Irish Sea Mud Belt (Belderson, 1964; Jackson et al., 1995) (Figures 5 and 6). Here, fine-grained sediments, referred to as the Mud Facies by Jackson et al. (1995), have been...
accumulating since the end of the last glaciation and form thicknesses of up to 40 m overlying glacial deposits (Coughlan et al., 2019; Jackson et al., 1995; Woods et al., 2019). These sediments are typically normally-consolidated, with low undrained shear strengths of up to 20 kPa (Coughlan et al., 2019). Such sediments, in significant thickness, are unlikely to support traditional monopile solutions. The Mud Facies has also been known to host gas, often leading to surface pockmark formation generating seabed instability (Belderson, 1964; Coughlan et al., 2019; Croker et al., 2005; Yuan et al., 1992).

3.3.2. Coarse-lag sediments

Coarse-lag sediments can represent areas where glacial sediments, exposed at the surface, have been reworked by modern wave and current processes removing finer material through winnowing. Often, the upper part of these deposits can be mobile with underlying layers forming a hard substrate that is difficult to penetrate. These upper sediments are Holocene in age, but the underlying units are typically classified as the Upper Till member and the Chaotic Facies of Jackson et al. (1995). The former is a glacial till that comprises sediment up to boulder class, whilst the Chaotic Facies is interpreted as glacial outwash sediments, predominantly gravels, with muds, sands and cobbles (Coughlan et al., 2019; Jackson et al., 1995).

3.3.3. Mobile sediment

The mobilisation of seabed sediments can affect the stability of offshore wind turbines and associated infrastructure in several ways. Sediment that is mobile in the form of migrating bedforms, such as sediment waves or sediment banks, can significantly change seabed-level. This change in seabed-level can either bury infrastructure or, in the case of connecting electrical cables, cause ‘free-spanning’ whereby seabed-level is lowered, and cables hang critically un-supported. Similarly, the removal of sediment in the immediate vicinity of wind turbine foundations by seabed erosion, or ‘scour’, can cause instability of the structure. Such issues were recorded at Ireland’s only offshore wind farm; Arklow Bank (Whitehouse et al., 2011). Therefore, understanding seabed sediment and bedform migration patterns are important to selecting sites that are not adversely affected over the lifetime of a project (Mellet et al., 2015).

3.3.4. Shallow gas

Gas in unconsolidated sediments is readily identified on seismic profiles as acoustic turbidity, acoustic blanking and enhanced reflection (Judd & Hovland, 1992). Examples of these have been recorded throughout the Irish Sea (Belderson, 1964; Coughlan et al., 2019; Croker, 1995; Croker et al., 2005; Jackson et al., 1995; Jones et al., 1992; Pantin, 1977; Van Landeghem et al., 2015; Yan et al., 1992). Often gas migrates to the seabed from deeper sources (up to km below the surface) where it can form gas escape structures (e.g. pockmarks) which destabilise the seabed (Yuan et al., 1992). Alternatively, in sandier conditions, seeping gas can precipitate carbonate minerals at the seabed forming methane-derived authigenic carbonate which cements the seafloor forming hard substrates (Judd et al., 2019; O’Reilly et al., 2014; Van Landegh et al., 2015).

3.3.5. Over-consolidated sediments

The advance of the Irish Sea Ice Sheet during the last glaciation deposited a layer of glaciogenic sediments, or till, typically directly on to bedrock (Jackson et al., 1995; Ó Cofaigh & Evans, 2001). This unit, referred to as the Upper Till member by Jackson et al. (1995), has been overridden by ice-loading and is often over-consolidated exhibiting undrained shear strength values of, on average, 185 kPa in the eastern Irish Sea (Mellet et al., 2015) and 148 kPa in the north Irish Sea (Coughlan et al., 2019). The heterogeneous nature of the Upper Till, comprising clasts from sand to boulder-size, and its over-consolidated nature would prove difficult for foundation piling.

3.3.6. Bedrock

The implications of variable bedrock levels have already been demonstrated at existing projects, such as Celtic Array, which was ultimately cancelled. Where bedrock is exposed at the surface it can form a surface which is difficult to pile (Mellet et al., 2015). In this study, bedrock was typically found exposed close to shore, in shallow water depths (Figure 7) The
presence of a hard, stable substrate like bedrock may favour wind turbine foundation types such as gravity base (Oh et al., 2018).

4. Summary

Previous technical assessments of the Irish EEZ in the Irish Sea as part of the OREDP have suggested the strong potential for offshore wind. The Main Map outlines the spatial distribution of some of the key geological features and processes which may constrain the future deployment of offshore wind energy in these areas. The East Coast (North) area is at the end of an active sediment transport route, and is an area where sediment is predominately being deposited rather than eroded (Figure 6). As a result, there are significant (40 m) accumulations of soft sediments that offer a potential geotechnical constraint (Figure 7). These sediments can also host gas (Figure 7).

The East Coast (South) has a variable morphology consisting of sediment banks and bathymetric deeps (Figure 8). Banks offer potentially shallow sites for construction, but are subject to morphodynamic change, whereas the deeps may offer future sites, previously unconsidered, for floating technology that are close to shore. However, the area is highly dynamic with mobile sediments, migrating bedforms and coarse-lag deposits which will need to be assessed for scour potential and seabed-level change (Figure 7).

The South Coast area assessed here is constrained by exposed bedrock close to shore and mobile sediment adjacent (Figure 7). Water depth drops off significantly here, making it more conducive to floating wind technology (Figure 1).

Seabed characterisation is a critical component of engineering design of offshore wind turbines, as well as environmental impact studies. A full geological and geotechnical classification of the Irish Sea is difficult to establish since this will vary significantly according to the type of renewable energy structure being considered and the localised seabed conditions. The data used in this study provides a snapshot of
the seabed at the time of collection and shows a highly dynamic environment with a significant degree of lateral and vertical heterogeneity in terms of seabed structure. It highlights the current understanding of geological conditions in the Irish EEZ in the Irish Sea and is recommended for use as a guide and should not replace a detailed site investigation. Overall, the water depths and seabed conditions in the Irish Sea are conducive to all of the various fixed substructure currently available for wind turbines as well as floating wind technology (Bosch et al., 2018; Oh et al., 2018). It is intended that this study and map may be used as part of any seabed zonation exercise carried out by the Irish Government in the marine spatial planning process. By doing so, it can significantly reduce the cost of future offshore wind deployment by helping to de-risk site selection and development.

**Software**

Bathymetric data were interrogated and interpreted using ESRI ArcGIS v10.6. Slope data were generated using the ESRI ArcGIS Spatial Analyst toolbox. Rugosity data were generated using IVS Fledermaus. Bathymetry Position index (BPI) data were generated using the ESRI ArcGIS toolbox ‘Benthic Terrain Modeler’. Digitisation and final data integration and map production were carried out using ESRI ArcGIS v10.6.

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