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Optimising Submarine Cable Routes from Offshore Wind
Farms – Site Suitability Mapping.

Thesis presented by

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for the degree of

Masters by Research

University College Cork

Department of Geography

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2024

Contents

Contents	i
Acknowledgements.....	iv
Abstract.....	v
List of Figures	vii
List of Tables.....	x
List of Acronyms.....	xi
1. Introduction.....	1
1.1. Aims and Objectives	4
1.2. Contributions of Thesis.....	4
1.3. Thesis Outline	5
2. Literature Review.....	6
2.1. Introduction.....	6
2.2. Offshore Wind Energy	7
2.3. Submarine Cables	9
2.4. Site Suitability.....	15
2.5. The Analytical Hierarchical Process in GIS	17
2.6. Site Suitability Mapping for Offshore Renewable Energy	19
2.7. Route Selection in GIS.....	23
2.8. Discussion	28
3. Methodology	32
3.1. Study Area.....	32
3.2. Data Collection	35
3.3. Criteria Layers	38
3.3.1. Bathymetry.....	39
3.3.2. Slope	41

3.3.3.	Substrate.....	43
3.3.4.	Distance to Grid	48
3.3.5.	Vessel Density	50
3.3.6.	Protected Sites and Exclusion Zones	52
3.4.6.1	Existing Cables or Pipelines	53
3.4.6.2	Natura 2000 Sites.....	55
3.4.6.3	Aquaculture Sites	57
3.4.6.4	Offshore Dump Sites.....	59
3.4.6.5	Shipwrecks	61
3.4.6.6	Military Exclusion Zones.....	63
3.4.	Software	65
3.5.	Data Sources	66
3.6.	Data Processing.....	67
3.7.	Multi-Criteria Decision-Making Analysis	75
3.8.	Site Selection	78
3.9.	Route Selection	82
3.10.	Sub-bottom Profile Data	83
4.	Results.....	88
4.1.	Multi-Criteria Decision-Making Analysis	89
4.1.1	Weighted Overlay Analysis.....	91
4.2.	Site Selection	96
4.2.1.	Sceirde Rocks.....	96
4.2.2.	South Coast DMAP.....	99
4.3.	Route Selection	101
4.3.1.	Sceirde Rocks.....	101
4.3.2.	South Coast DMAP.....	104
4.4.	Sub-bottom Profile Analysis	110

5.	Discussion	120
5.1.	Submarine Cable Route Feasibility: A Multi-Criteria Decision-Making Approach and its Implications for Offshore Energy Site Selection.....	120
5.2.	Optimal Seabed Regions for Submarine Cables: Economic vs. Environmental Considerations.....	122
5.3.	Least Cost Path Cable Routes: Informing Offshore Windfarm Site Selection	125
5.4.	Optimising Submarine Cable Burial: Sub-Bottom Profile Analysis.....	128
5.5.	Limitations	131
5.6.	Recommendations for Further Study	133
6.	Conclusion	136
	References.....	137

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Abstract

The Irish Government's Climate Action Plan aims to increase renewable energy generation capacity to 22 GW by 2030, with at least 5 GW of this to be produced by offshore windfarms. The potential to harness and develop this resource is significant; however not all areas offshore are suitable. Moreover, not all routes from windfarms to land are suitable for the submarine cables needed to transfer the energy produced offshore back to the onshore grid.

This project leverages geospatial analysis to identify optimal routes for submarine export cables, enhancing our understanding of marine and coastal geomorphology and the potential hazards associated with these environments. This research is focused on the South and West coasts of Ireland, a region with substantial potential for offshore wind energy development, particularly floating wind turbine platforms.

A comprehensive geospatial repository of publicly available data was compiled, incorporating key features relevant to submarine cable route feasibility. These criteria layers include bathymetric, geological and ecological data, as well as information on human activities in the area, to assess the potential hazards to a submarine cable within a particular region. Criteria weights were calculated for two scenarios using the Analytical Hierarchical Process, based on expert opinion, while a third scenario applied equal weighting to each layer to evaluate the impact of these weights

The resulting maps classify regions off the South and West coasts of Ireland into zones of suitability for submarine export cables. A Least Cost Path Algorithm was then implemented in ArcGIS Pro along these surfaces, which identified the most optimal routes for each scenario. Particular focus was paid to those parts of the study area where there are current plans for offshore wind energy development, as identified during phase I and II of the Irish Governments Offshore Renewable Energy Development Plan.

In a novel application, INFOMAR sub-bottom profile data was analysed within two key regions off the South Coast highlighted from the route selection analysis. This study presents some of the first examples of utilising this openly available dataset for spatial planning of offshore infrastructure. The resulting sediment thickness maps derived from this analysis facilitated routing through areas where seabed sediment depths are adequate for cable burial, thereby minimising the risk of damage from external hazards that could shorten the lifespan of the cable and lead to costly repairs.

The findings detailed within this study provide a useful tool for policy makers and developers in the feasibility stages. In a broader context, given the vast size of Ireland's offshore territory, these findings can be applied by planners to create objective and standardised cable routes having both immediate economic and environmental benefits. The use of publicly available data herein can reduce the reliance on extensive geophysical surveys, which are not only expensive and time-consuming but also can be environmentally detrimental, particularly due to the impact of anthropogenic sound on marine mammals. By lowering the costs associated with marine surveys and identifying optimal routes that reduce the risk to submarine cables, this approach can encourage international developers to invest in offshore energy in Ireland, ultimately supporting the rapid and widescale rollout of renewable energy needed to meet national targets. The innovative approaches and datasets detailed in this thesis not only advance the precision of submarine cable routing but also establish a replicable framework for offshore wind energy projects, thereby contributing to the efficient and sustainable growth of global renewable energy infrastructure.

List of Figures

Figure 1.1: Ireland's Marine Territory	2
Figure 2.1: Layout of a typical offshore wind farm; wind turbines (a), intra-array cables (b), export cables (c), offshore HVAC substation (d), offshore HVDC substation (e), onshore substation (Rodrigues et al., 2016).	9
Figure 3.1: OREDP Assessment Zones, DCCAE (2014)	33
Figure 3.2: Study Area - South and West Coast.....	34
Figure 3.3: South and West Coast Bathymetry (EMODnet, 2022b).....	39
Figure 3.4: South and West Coast Seabed Slope, derived from INFOMAR (2023a).....	41
Figure 3.5: South and West Coast Seabed Classification Map (INFOMAR, 2023c)	43
Figure 3.6: Folk Sediment Classification Scheme (Kaskela et al., 2019).....	45
Figure 3.7: South and West Coast Exposed Bedrock (Arosio et al., 2023)	46
Figure 3.8: South and West Coast Coastal Substations (≥ 220 kV) (EirGrid, 2023c)	48
Figure 3.9: South and West Coast Average Vessel Density (EMODnet, 2022d).....	50
Figure 3.10: South and West Coast Cables and Pipelines.....	53
Figure 3.11: South and West Coast Natura 2000 Sites. (NPWS, 2019; 2023a; 2023b).....	55
Figure 3.12: South and West Coast Aquaculture Sites (Department of Agriculture, Food and the Marine, 2018).....	57
Figure 3.13: South and West Coast Offshore Dump Sites - Active and Inactive (EPA, 2023)	59
Figure 3.14: South and West Coast Shipwrecks (DHLGH, 2023a; INFOMAR, 2023b)	61
Figure 3.15: South and West Coast Military Exclusion Zones (EMODnet, 2022c).....	63
Figure 3.16: Reclassified Bathymetry Layer	69
Figure 3.17: Reclassified Slope Layer	70
Figure 3.18: Reclassified Substrate Layer	71
Figure 3.19: Reclassified Distance to Grid Layer.....	72
Figure 3.20: Reclassified Vessel Density Layer	73
Figure 3.21: Reclassified Protected Sites and Exclusion Zones Layer.....	74
Figure 3.22: Location of Sceirde Rocks Offshore Wind Farm Project and South Coast DMAP	79
Figure 3.23: Sceirde Rocks Offshore Windfarm Project (Maritime Area Regulatory Authority, 2022)	80
Figure 3.24: South Coast DMAP Site with Potential Offshore Substation and Landfall Locations (DHLGH, 2023b)	81

Figure 3.25: Available and Processed SBP Track lines – South Coast DMAP	84
Figure 3.26: Line_19_230413.092017.sgy from survey CV13_01 – Pre-processing	85
Figure 3.27: Line_19_230413.092017.sgy from survey CV13_01 - bottom tracked with gains applied.....	85
Figure 3.28: Line_19_230413.092017.sgy – Post Processing.....	86
Figure 3.29: Example of a Digitised Seismic Reflector	86
Figure 4.1: Economic Scenario - Suitability Surface.....	92
Figure 4.2: Environmental Scenario - Suitability Surface	93
Figure 4.3: Equal Weighting Scenario – Suitability Surface	94
Figure 4.4: Pie Charts representing the percentage of suitability for each scenario.....	95
Figure 4.5: Sceirde Rocks Project Area Site Suitability Analysis – Economic Scenario	97
Figure 4.6: Sceirde Rocks Project Area Site Suitability Analysis – Environmental Scenario	97
Figure 4.7: Sceirde Rocks Project Area Site Suitability Analysis – Equal Weighting Scenario	98
Figure 4.8: South Coast DMAP Site Suitability Analysis – Economic Scenario	99
Figure 4.9: South Coast DMAP Site Suitability Analysis – Environmental Scenario.....	100
Figure 4.10: South Coast DMAP Site Suitability Analysis – Equal Weighting Scenario.....	100
Figure 4.11: Sceirde Rocks - Shortest Routes.....	101
Figure 4.12: Sceirde Rocks – Resulting SEC Routes from LCPA.....	102
Figure 4.13: South Coast DMAP – Shortest Routes.....	104
Figure 4.14: South Coast DMAP – Economic Scenario LCPA Results	105
Figure 4.15: South Coast DMAP – Environmental Scenario LCPA Results.....	105
Figure 4.16: South Coast DMAP – Equal Weighting Scenario LCPA Results.....	106
Figure 4.17: South Coast DMAP – Top Five Lowest Overall Cost Routes for each Scenario	108
Figure 4.18: South Coast DMAP – Top Five Lowest cost-per-km Routes for each Scenario	109
Figure 4.19: Location of Sub-bottom Profile Trackline L0098_170916.134457 from survey CV16_05 (a) and Sub-bottom Profile view (3X Vertical Exaggeration) with examples of Sediment Waves and Seismic Reflectors (b)	110
Figure 4.20: Location of Sub-bottom Profile Tracklines (a) and Sub-bottom Profile views (3X Vertical Exaggeration) with examples of Seismic Reflectors R3 and R4 (b), Digitised Seismic Reflector R3 with Hyperbola Corresponding with Outcropping Bedrock (c), Digitised Seismic Reflectors R2, R3 and R4 (d), and Digitised Seismic Reflectors R1 and R2 (e).....	112

Figure 4.21: Seismic Unit Thickness Point data	114
Figure 4.22: South Coast DMAP - EBK Interpolation Grids	114
Figure 4.23: Reclassified Sediment Thickness Map - Suitability Scores	115
Figure 4.24: LCPA Routes for DMAP_Waterford and DMAP_Wexford.....	116
Figure 4.25: 3D view of Digitised Seismic Reflectors, Bathymetry and LCPA Routes.....	117
Figure 4.26: Results of LCPA on combined Sediment Thickness and Protected sites and Exclusion zones surface.....	118
Figure 4.27: Optimal SEC Routes within the South Coast DMAP	119
Figure 5.1: Economic Scenario - Most Suitable Regions for SECs	123
Figure 5.2: Optimal SEC Routes with Landfall sites surrounding Cork City	134
Figure 5.3: Optimal SEC Routes with Landfall sites east of Dungarvan, Co. Waterford.....	135

List of Tables

Table 3.1: Criteria Affecting the Feasibility of Submarine Cables as Identified in Existing Literature.....	36
Table 3.2: Criteria Layer Data Type and Sources	66
Table 3.3: Criteria Layer Classification Values	68
Table 3.4: The Fundamental Scale, adapted from Saaty (1987)	76
Table 4.1: Economic Scenario - Pairwise Comparison Matrix.....	90
Table 4.2: Environmental Scenario - Pairwise Comparison Matrix	90
Table 4.3: Equal Weighting Scenario.....	90
Table 4.4: Results of Site Suitability Analyses - Sceirde Rocks.....	96
Table 4.5: Results of Site Suitability Analyses- South Coast DMAP.....	99
Table 4.6: Sceirde Rocks - Results of LCPA	103
Table 4.7: Results of LCPA - South Coast DMAP	107
Table 4.8: Sediment Thickness Suitability Score.....	115
Table 4.9: LCPA Results for DMAP_Waterford and DMAP_Wexford.....	117
Table 4.10: LCPA Results for DMAP_Waterford and DMAP_Wexford on combined Sediment Thickness and Protected sites and Exclusion zones surface.....	119
Table 5.1: Costs of Optimised SEC Route from Sceirde Rocks Offshore Windfarm.....	125
Table 5.2: Costs of Optimised SEC Routes within South Coast DMAP	130

List of Acronyms

ACER – The European Union Agency for the Cooperation of Energy Regulators

AHP – Analytical Hierarchical Process

AIS – Automatic Identification System

BERR – Department for Business Enterprise and Regulatory Reform

CI – Consistency Index

DCCAE –Department of Communications, Climate Action & Environment

DECC –Department of the Environment, Climate and Communications

DHLGH – Department of Housing, Local Government and Heritage

DMAP – Designated Maritime Area Plan

EBK – Empirical Bayesian kriging

EC – Council of the European Union

EEZ – Exclusive Economic Zone

EPA – Environmental Protection Agency

EMODnet – European Marine Observation and Data Network

EU – European Union

FMM – Fast Marching Method

GEBCO – General Bathymetric Chart of the Oceans

GIS – Geographic Information System

GSI – Geological Survey of Ireland

GW – Gigawatt

GWEC – Global Wind Energy Council

HVAC – High-Voltage Alternating Current

HVDC – High-Voltage Direct Current

ICPC – International Cable Protection Committee

IEA – International Energy Agency

INFOMAR – The Integrated Mapping for the Sustainable Development of Ireland’s Marine Resource

ISSGM – Irish Shelf Seabed Geomorphological Map

kHz - Kilohertz

km – Kilometre

kV - Kilovolt

LCPA – Least Cost Path Analysis

MBES – Multibeam Echosounder

MCDA – Multi-Criteria Decision-Making Analysis

MPA – Marine Protected Area

MWh – Megawatt Hour

NHA – National Heritage Area

NMS – National Monuments Service

NPWS – National Parks and Wildlife Service

OWF – Offshore Wind Farm

ORE – Offshore Renewable Energy

OREDPA – Offshore Renewable Energy Development Plan

ORESS – Offshore Renewable Energy Support Scheme

RI – Random Index

RQ – Research Question

SA – Simulated Annealing

SAC – Special Area of Conservation

SBP – Sub-Bottom Profile

SEAI – Sustainable Energy Authority of Ireland

SEC – Submarine Export Cable

SPA – Special Protection Area

SU – Seismic Unit

UK – United Kingdom

UTM – Universal Transverse Mercator

WGS – World Geodetic System

1. Introduction

In 2020, the European Union endorsed the European Green Deal, which outlines ambitious objectives aimed at achieving net zero greenhouse gas emissions by 2050 (European Commission, 2019). Realising this goal presents significant challenges for individual nations, as entire industries will need to be restructured to transition away from reliance on fossil fuels. This transformation requires substantial investment, policy changes, and technological advancements.

Despite these challenges, there are enormous opportunities for growth in sectors leveraging innovative and sustainable technologies. Renewable energy is a prominent example, offering potential for job creation, economic development, and environmental benefits. The shift to renewable energy sources such as wind, solar, and hydroelectric power is not only essential for reducing emissions but also for fostering energy independence and resilience in the face of global energy market fluctuations.

As of 2022, the energy sector accounted for 56% of Ireland's total greenhouse gas emissions, with agriculture the second highest polluter at 38% (SEAI, 2023b). Within the energy sector, emissions can be categorized into three primary modes of consumption: Heat, Transport, and Electricity, accounting for 36%, 34%, and 30% of emissions, respectively (SEAI, 2023a). Ireland's national plans for reducing these emissions are detailed recently in the Irish Government's Climate Action Plan (DECC, 2023a). This details a roadmap to net-zero emissions by 2050, with initial goals of producing 80% of the nation's electricity demand through renewable energy sources by 2030 (DECC, 2023a). This will not only reduce carbon emissions from the electricity sector itself, but as electrification of transport and heat are rolled out, further emission reductions will be facilitated by renewable energy.

Ireland's current renewable energy infrastructure generated 39% of electricity in 2023, with 35% of this from onshore wind farms (SEAI, 2023a; WEI, 2024.) With widespread electrification of other sectors, the electricity demand is forecasted increase by 23-47% by 2030, and to double by 2050 (EirGrid, 2019; EirGrid, 2023a). Although onshore wind and solar energy will contribute to meeting these demands, it is evident that offshore wind is the technology that holds the greatest potential for achieving the scale of development required for Ireland. A large-scale, fast-paced rollout of offshore wind could not only meet domestic demands, but eventually surpass them, positioning Ireland as a net exporter of energy.

With a total area of 880,000 km², Ireland's designated continental shelf is roughly ten times larger than its landmass size and one of the largest in Europe (DCCAE, 2014). Within this territory exists a vast, and mostly untapped, wind energy resource. Current gross technical resource estimates indicate 641 gigawatts (GW) of offshore wind energy potential, 34.8 – 39 GW of which could be harnessed by wind turbines without adverse environmental effects (DCCAE, 2014; DECC, 2023a). To put that in perspective, a 1 GW windfarm in the UK typically generates enough electricity to power approximately 1 million homes (Clark, 2019).

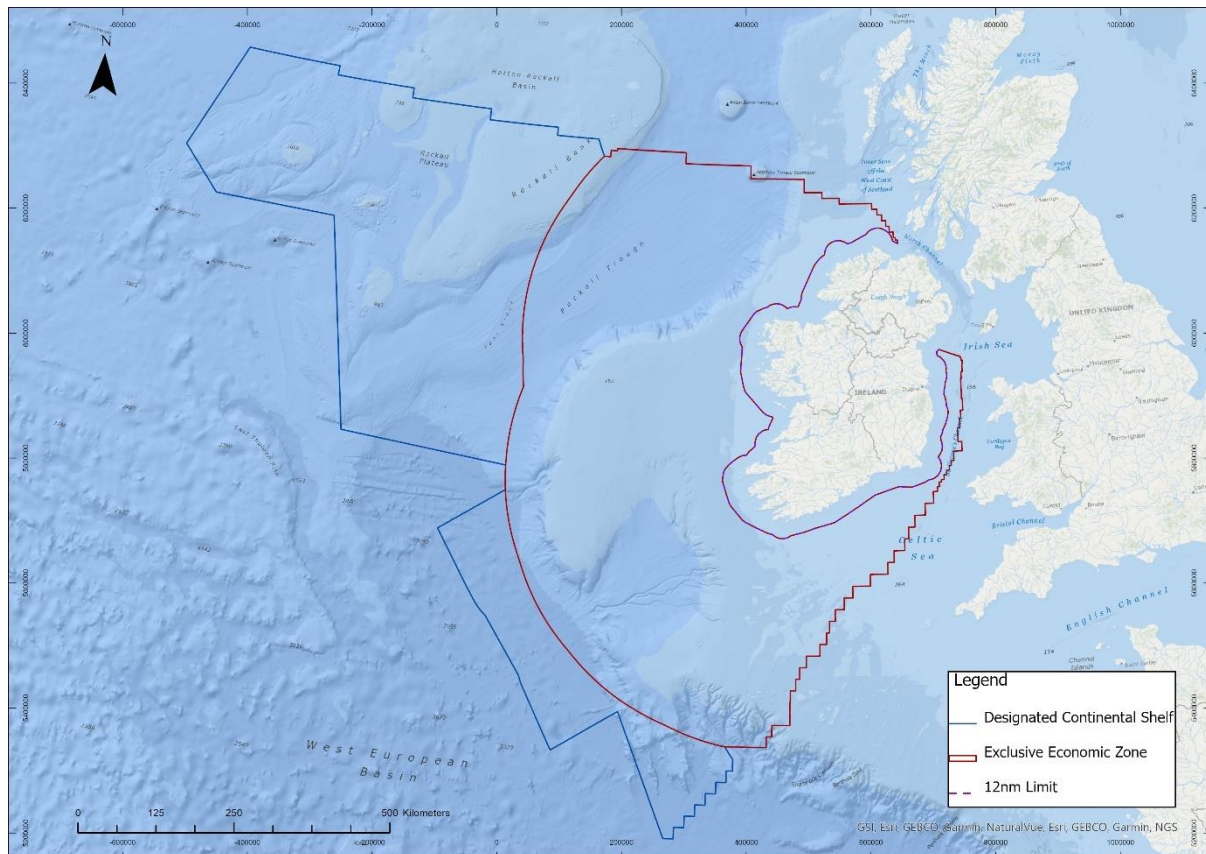


Figure 1.1: Ireland's Marine Territory

Ireland's first offshore windfarm (OWF), the Arklow Bank Wind Park, was completed in 2004. At the time, this windfarm had some of the largest turbines in the world which had a combined energy generation capacity of 25 MW (Joshti *et al.*, 2018). Twenty years on in 2024, despite major developments in the onshore wind energy industry, Arklow Bank remains the only OWF in Ireland. This, however, is set to change in the coming years.

The 2023 Climate Action Plan sets forth goals of at least 5 GW of offshore wind energy capacity by 2030, and up to 37 GW by 2050, emphasising the enormous potential for this marine resource (DECC, 2023a). Achieving these ambitious targets requires huge buildouts in infrastructure, both offshore in the wind farms themselves, and onshore in the ports,

manufacturing centres and electrical distribution networks. The transition to an electrical grid based on renewable energy sources demands a significant investment of capital and human resources. However, reaching the 2050 goals for offshore wind energy could benefit the Irish economy by some €38 billion (BVG Associates, 2024). Additionally, an estimated 19,500 - 30,000 full time jobs will be required within the industry by 2030 to meet the 5 GW target (BVG Associates, 2024).

The potential to harness and develop this resource is clearly significant and of vital importance to Ireland's energy security; however not all areas offshore are suitable for OWFs. Moreover, not all routes from OWFs to land are suitable for the submarine export cables (SECs) that are required to transfer the energy produced offshore back to the onshore grid. To date, High Voltage Alternating Current (HVAC) cables rated up to 220 kV have typically been installed in OWFs around Europe (Red Penguin Associates Ltd., 2012). These cables are composed of three copper core conductors, with steel wire and cross-linked polyethylene armouring (BVG Associates, 2019). A typical 220 kV SEC is 320 mm in diameter and has a mass of roughly 110 kg/m (BVG Associates, 2024). Systems using High Voltage Direct Current (HVDC) technology can also be applied to OWFs, however the costs savings of HVDC when compared to HVAC only become evident at distances between substations of greater than 80-100 km (BVG Associates, 2019).

SECs are installed by specialised cable laying vessels, with the cable generally buried within the seabed sediments using subsea ploughs, or jetting mechanisms installed on remotely operated vehicles (Carter, 2009). The cost associated with cables and cable installation is in the order of 11-14% of overall capital expenditure for an OWF (BVG Associates, 2019). However, cables are among the most vulnerable components of an OWF, with 70-80% of the costs related to insurance claims for OWFs linked to cable failure (Anderson, 2016). A reported 90 submarine cable incidents occurred globally between 2010-2017, accounting for a total of €350 million in insurance claims (Anderson, 2016). Therefore, understanding the most suitable sites for SECs can lower the risk and expense associated with cable failures.

This project is focused on SECs from OWFs, though the same principles apply to SECs associated with other forms of offshore renewable energy (ORE), such as wave or tidal energy. Site Selection for ORE projects will be assessed based on various factors, such as the energy resource potential, environmental and societal impacts, infrastructure availability and regulatory requirements (BVG Associates, 2019). To date, several studies have focused on site

suitability mapping for ORE within Ireland’s Marine Territory (e.g. Coughlan *et al.*, 2015; Murphy *et al.*, 2016; Cummins and McKeogh, 2020; Butschek *et al.*, 2023). No studies to date have considered the suitability of the Irish seabed for SECs, with SEC cable routes generally designed on a case-by-case basis. By analysing large portions of Ireland’s coastline, site suitability mapping for SECs can provide planners and developers with a comprehensive understanding of the best locations for cable installation, thereby optimising the integration of offshore renewable energy into the national grid.

1.1. Aims and Objectives

This research is focused on the South and West Coasts of Ireland, an area under intense development for offshore wind energy. This study aims to utilise geospatial analysis to identify the most suitable regions offshore for SECs within the study area and establish a workflow for SEC route selection. By identifying all the relevant criteria for optimal conditions in the seabed, a multi-criteria decision-making analysis (MCDA) can be applied to amalgamate these criteria into a unified suitability surface. Subsequently, an automated route selection algorithm can be implemented in a Geographic Information System (GIS), creating SEC routes which preferentially select the areas with the most suitable seabed conditions and avoid potentially hazardous or environmentally sensitive areas. In addition to optimising the routes themselves, selection of sites for associated infrastructure can also be enhanced.

1.2. Contributions of Thesis

This thesis seeks to provide detailed insights into the ideal seabed conditions for SECs along the South and West Coasts of Ireland. However, these findings are not limited to this specific region and can be extended to comparable maritime areas surrounding Ireland and globally. The thesis details a workflow that planners and developers of ORE projects can implement to highlight prime locations for SECs around the coastline and to quickly and efficiently design SEC routes from proposed or existing offshore locations.

A significant contribution of this thesis is the utilisation of sub-bottom profile (SBP) data obtained by INFOMAR, Ireland’s seabed mapping programme. The results of this analysis provides a novel and valuable dataset pertaining to seabed sediment thickness for two key segments of the study area, located off Ireland’s South Coast. By integrating this dataset, cable routes can be further optimised by preferentially selecting areas with suitable thicknesses of sediment for cable burial, which is deemed the most cost effective and least environmentally

impactful cable protection strategy (BERR, 2008). This innovative use of openly available SBP data enhances the precision of submarine cable routing, allowing planners to concentrate on specific areas at an early stage, without requiring additional expensive and time-consuming marine geophysical surveys. This approach not only supports sustainable development practices but also offers practical solutions for development of Ireland's offshore renewable energy projects, facilitating the realisation of national targets.

1.3. Thesis Outline

Chapter 2 of this thesis provides a literature review, summarising the work of previous authors to offer a comprehensive understanding of past research in the field of site suitability analysis for offshore wind energy, multi-criteria decision making, and cable route planning. It also identifies existing gaps in the literature where further study is warranted. Chapter 3 provides an overview of the data utilised in the project, including details on data normalisation. It also describes the methodology used for determining site suitability, the route selection analysis, and the processing of the SBP data. The results of these analyses are presented and detailed in Chapter 4. The final chapter, Chapter 5, the location and distribution of the most suitable sites and routes are further examined and discussed, along with the potential impacts on ORE spatial planning in Ireland. It also addresses any limitations of the current study and proposes directions for future research.

2. Literature Review

2.1. Introduction

This literature review examines the current research on optimal environmental and seabed conditions, as well as the economic factors necessary for planning viable submarine cable routes. This will be achieved by an in-depth examination of similar studies, as well as industrial standards and recommendations.

This review aims to describe the theoretical underpinnings of site suitability mapping, geospatial multi-criteria decision-making analyses, and route selection tools in Geographic Information Systems (GIS). It will assess the strengths and limitations of various methodologies and relate their applicability to the scope of the current study. Previous studies examining the INFOMAR (Integrated Mapping for the Sustainable Development of Ireland's Marine Resource) dataset, particularly those which utilised the existing sub-bottom profile (SBP) data, are also reviewed. The chapter concludes with a summary of the current state of knowledge, highlighting gaps that inform each research question (RQ) which is to be addressed in this thesis.

2.2. Offshore Wind Energy

A wind farm is a collection of rotary turbines that are propelled by the kinetic energy of the wind (Arshad and O’Kelly, 2012). This rotational movement propels a driveshaft, which in turn generates electricity through the process of electromagnetic induction within a generator, resulting in the production of an electric current (Arshad and O’Kelly, 2012). Therefore, whether a wind farm is constructed onshore or offshore, the fundamental principles guiding its success are the same.

Humans have utilised wind power for thousands of years, with historical records dating as far back as 3100 BCE, when Egyptians navigated the Nile River using wind-driven vessels (Pasqualetti *et al.*, 2004). The earliest known evidence of harnessing wind power on land comes from modern day Iran, where rudimentary windmills were employed in grinding grain and used in irrigation to pump water from streams (Pasqualetti *et al.*, 2004). The first functional electricity-generating wind turbine was created in Ohio, USA, in the late 1800s, operating successfully for 15 years, though its cost and complexity prevented replication (Pasqualetti *et al.*, 2004). This highlights the longstanding issue of identifying both an environmentally suitable location, as well as an economically viable design, for wind energy technologies.

The first commercial-scale wind farm was commissioned by Denmark in 1906, consisting of forty turbines (Pasqualetti *et al.*, 2004). To this day, Denmark has continued this tradition of pioneering wind energy power generation. In 1991, Denmark built the world’s first offshore wind farm (OWF), the Vindeby Offshore Wind Farm, which consisted of eleven 450 kW turbines located 2 km from the coastline in waters of up to 4 m depth (Rodrigues *et al.*, 2015). Denmark is now considered a global leader in wind energy and the wind energy industry in Denmark provided 35,400 direct and indirect jobs in 2018 (Van Est, 2022).

Due to the essentially boundless resource of wind and the scalability of OWFs, many countries have prioritized offshore wind energy production as a means to mitigate their reliance on fossil fuels (Rodrigues *et al.*, 2015). As of 2022 there was a total of 64.3 GW of installed offshore wind energy capacity, with China, the United Kingdom and Germany the top markets for offshore wind (GWEC, 2023). A projected 380 GW of global offshore wind capacity is expected to be built by 2032 (GWEC, 2023). To maximise energy production whilst also reducing visual and environmental impacts, these projects are trending towards larger areas and bigger turbines located in deeper waters, further from the coast (Igwemezie *et al.*, 2019; Rodrigues *et al.*, 2015).

Wind energy is set to play a pivotal role in achieving the EU and United Nations goal of Net Zero Emissions by 2050, outlined in the Paris Agreement (UNFCCC, 2015). According to the International Energy Agency (IEA), a significant increase in global wind energy capacity is required to meet this goal, with over 20% of this electricity production forecasted to come from offshore wind (IEA, 2022).

Due to its extensive offshore territory and reliably high wind speeds, Ireland is well-situated for the development of OWFs. This is reflected by the Irish Government's ambitious target of 37 GW of offshore wind energy capacity to be in production by 2050 (DECC, 2023a). "Blueprint for Offshore Wind in Ireland 2020-2050: A Research Synthesis", published as part of the EirWind project, is a pivotal piece of research which was concluded in 2020 by MaREI, a research centre based in University College Cork, Ireland (Cummins and McKeogh, 2020). This study outlines a roadmap for reaching Ireland's offshore wind energy targets. It examined three regions of Ireland's offshore territory: the Irish Sea, the Celtic Sea and the Atlantic. The study assessed the most appropriate wind energy technology for each location and provided estimates of potential energy capacity, and Levelized Cost of Energy figures, for each zone. It also discussed the challenges associated with the widescale deployment of offshore wind in Ireland, including the potential impacts to other marine users and the environment. Additionally, gaps in knowledge were identified, such as incomplete, high-resolution mapping coverage of the seabed. A lack of detailed information on the seabed sediment was also highlighted, noting very little sub-bottom detail available and an absence of standardisation across existing datasets.

The study reveals that the rapid expansion of offshore wind energy in Ireland requires meticulous spatial planning to ensure a reliable supply of electricity whilst also reducing environmental and social impacts. Submarine export cables (SECs) are a crucial component in transmitting the generated electricity from OWFs to onshore grids. This technology ensures that the increased capacity from larger and more remote wind farms can be effectively integrated into the existing power network, supporting the global transition to renewable energy.

2.3. Submarine Cables

The electricity generated by offshore wind turbines is transferred via a series of submarine cables which fall into two primary categories, intra-array cables and export cables (Figure 2.1). Intra-array cables form an inter-connected network that conveys the electricity from the turbines to an offshore sub-station (Cazzaro and Pisinger, 2022). Here, the voltage is increased before being transmitted back to the onshore grid via an SEC. The number of SECs per windfarm may vary depending on the scale and energy capacity of the OWF, however there will typically be more than one SEC to allow for transmission redundancy (Red Penguin Associates Ltd, 2012). All cables must be protected from external hazards, which is primarily achieved by burial within the seabed sediments, typically to depths of 1-4 m (BVG Associates, 2019).

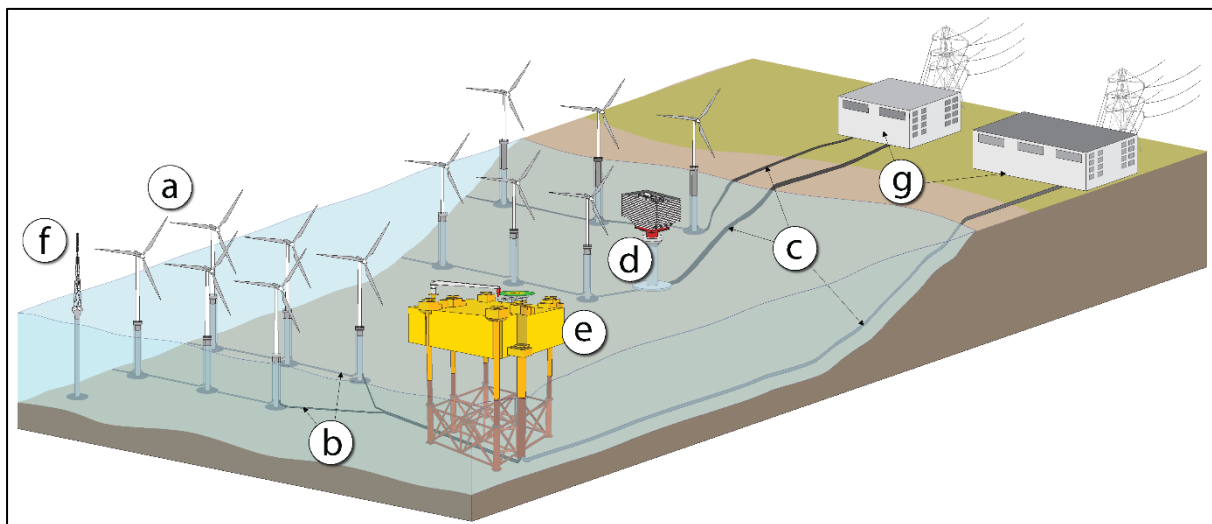


Figure 2.1: Layout of a typical offshore wind farm; wind turbines (a), intra-array cables (b), export cables (c), offshore HVAC substation (d), offshore HVDC substation (e), onshore substation (Rodrigues et al., 2016).

A significant portion of the literature on submarine cables focuses on telecommunication cables, which are the most widely deployed type of submarine cable globally. These cables transfer 99% of transoceanic digital communications and function as the foundational infrastructure of the global internet (Gallagher, 2022). Although telecommunication and export power cables differ slightly in diameter and overall installation length, the methods for routing, installation and associated hazards in marine environments are similar.

The International Cable Protection Committee (ICPC) is a non-profit organisation, established to advocate for the safeguarding of international telecommunications and submarine power

cables from both human and natural hazards. In addition to its primary objectives, the ICPC publishes guidance on various aspects related to submarine cables. Such publications include ICPC Recommendation No.9 (2015), which outlines best practices for planning a cable route. This encompasses compiling a detailed database of the geological, oceanographic, and climatological information pertinent to the proposed route. Additional considerations include assessing commercial operations such as shipping or fishing, identifying potential obstructions such as shipwrecks or artificial reefs, and accounting for biological factors, such as Marine Protected Areas (MPAs) and fish spawning sites.

Additional publications from the ICPC include ICPC Recommendation No.11 (2023), specifying the essential information to be included within a route, and ICPC Recommendation No.18 (2020), detailing the minimum requirements for hydrographic and geophysical surveying of a route. The latter report recommends seabed mapping surveys using a Multibeam Echosounder (MBES), side-scan sonar and magnetometer. Sub-bottom profiling is also recommended to determine the vertical extent of the seabed sediments. A survey corridor ranging in width from 500 to 1000 m is advised for all segments of the route, except for the inshore section. This is the section closest to the landfall site, in water depths of less than 20 m, where a narrower corridor is deemed acceptable. In the shallower regions, which are not accessible by the inshore survey vessel (depths of less than approximately 3 m), a diver swim survey may be required. Once these surveys are completed, a cable burial assessment may be initiated.

Cables are buried to protect against hazards, the most common of which are anthropogenic (ICPC, 2021). In a report released by the ICPC in 2021, an analysis of records documenting over 5,000 submarine cable faults since 1959 revealed that the most common causes were fishing-related incidents and anchor strikes. These two factors accounted for a significant percentage of the total faults, ranging from 40.8% to 15.8%, respectively (ICPC, 2021).

The Department for Business Enterprise and Regulatory Reform (BERR) in the United Kingdom (UK) released a report in 2008 describing the techniques of cable deployment and environmental effects. Although submarine power cable technologies have advanced somewhat since 2008, the protection methods remain applicable today. The methods described include cable burial by ploughs, jetting systems and rock wheel cutters. The report provides recommendations on cable burial depths based on variable seabed conditions and risks, with particular focus on the risks posed by fishing gear. These burial depths range from 0.4 m in

very hard ground (e.g. stiff clay or rock) to as much as 9.2 m in very soft sediment areas (e.g. mud or silt) where there is a risk of anchor strikes. Additional information in the report details alternative cable protection methods where burial is not possible. These include rock dumping, frond mattresses or concrete mattresses. The latter options are favoured by the fishing industry as there is less chance of damage to fishing gear when compared with rock dumping. Burial is the preferred method of protection over these options, since all require the introduction of foreign material into the marine environment, which could have potentially harmful consequences. However, the report concludes that there is a gap in the research related to the environmental effects of sediment plumes which may form during certain burial methods such as jetting or dredging.

A report by the Carbon Trust (2015) details a methodology for optimising cable burial depth for submarine cables in UK waters through the development of a Cable Burial Risk Assessment. The aim is to reduce costs by providing a minimum burial depth along a designated cable route through an iterative probabilistic approach of assessing the risk to the cable at any location along the route. The report highlights that the main risks are anchor strikes and fishing gear, with the former presenting the greater risk due to increased penetration depths. Areas of mobile sediment may also pose a risk, as locally higher seabed gradients associated with sandwaves or megaripples could lead to free spanning. Free spans occur when a section of cable becomes exposed and unsupported on the seabed, leaving it vulnerable to fishing gear and other hazards.

Carter *et al.* (2014) provide a comprehensive overview of submarine cables, primarily focusing on telecommunication cables but also touching on SECs. The process of cable burial is discussed, with mechanical ploughing being noted as the most common. This technique involves a plough towed from a ship creating a furrow in the seabed in which the cable is placed and then simultaneously covered over, using the same equipment, or allowed to bury naturally through sedimentation. A plough may disturb a strip of seabed ranging from 2-4 m. Jetting is often used for cable burial in areas where ploughing is not feasible, though it may create wider disturbance zones due to turbid plumes, especially in softer sediments. The chapter also discusses environmental regulations, highlighting that submarine cable installation and repair should not be considered marine pollution as defined by the United Nations Convention on the Law of the Sea (UNCLOS, 1982). The authors also suggest that in an area with several submarine cables, a Cable Protection Zone may be designated. Such a zone could also function

as an MPA (Marine Protection Area), as activities that pose risks to cables, such as anchoring, trawling, or deep-sea mining, are also environmentally impactful.

El Mountassir and Strang-Moran (2018) examine the trends in submarine power cables for offshore wind farms within the UK from 2003, to the time of writing. The study revealed significant growth in submarine power cable technology, a consequence of the rapid expansion of the offshore wind industry during this period. The trends reveal an increase in the voltage levels conveyed by SECs, with 80% of OWFs in Europe using SECs of higher than 200kV by 2018. This trend is a result of the recent emergence of larger projects, situated farther from the coastline compared to the earliest constructed windfarms. The authors note the high-risk aspect of submarine cables, with cable failures accounting for 75-80% of costs for insurance claims for offshore windfarms. At the time of publication, 88% of known cable failures in the UK were related to SECs, with the manufacturing and installation of these cables reported as the phase most frequently associated with failure. The significant costs of these cable failures are also emphasized, encompassing both the expense for cable repairs and the lost revenue due to wind farm downtime.

Taormina *et al.* (2018) conducted a review of the literature concerning submarine power cables and their potential impacts on marine environments. The authors discuss physical impacts, such as the reworking of seabed sediments during cable installation, which may disturb benthic communities. They also describe the potential effects of sediment plumes and anthropogenic noise generated during installation, though these effects are generally localised. Similar to Carter *et al.* (2014), the authors concluded that the environmental impacts of submarine cables and their installation are minor compared to ongoing human activities like trawling, due to the short duration of installation and occasional maintenance or repairs. However, the authors note that the effect of electromagnetic fields induced from power cables on marine species, particularly elasmobranchs such as sharks and rays, is not well studied.

Others have looked at the relationship between seabed composition and submarine cables. Cao *et al.* (2021) analysed the effect of multi-layered sediments on the thermal properties of high-voltage submarine power cables. These cables are typically coated with a cross-linked polyethylene insulation which can deteriorate at temperatures exceeding 90°C, therefore understanding the transmission of heat through cables and their surrounding sediment is crucial to ensuring safe operation. Examples are given of high-voltage interconnector projects in Europe which ranged from 23-580 km in length and were typically buried to depths of 0.6-3

m, with one instance of a cable buried at 5-7 m depth. For the study, a three-core, 220 kV HVAC cable was buried in a multi-layered soil and an electromagnetic heat source was introduced into the cable. Analysis was conducted on the impact of sediment characteristics, including grain size, permeability and burial depth, on the thermal behaviour of the cables. The results indicate that burial in permeable sediments, such as sand and coarse sediments, is preferable for heat dissipation, with lower burial depths of 0.5-1 m recommended in less permeable sediments. These findings underscore the importance of considering sediment composition when devising a cable burial strategy, with increased longevity of the cable insulation expected when buried in coarse, sandy sediments.

Moore *et al.* (2021) aimed at developing more comprehensive guidelines to cable burial depth by analysing the varying penetration depths of anchors in sandy sediments. The study analysed the Burial Protection Index, first proposed by Mole *et al.* (1997), which provides recommended burial depths depending largely on the sediment type. The authors emphasize that the depths recommended by the Burial Protection Index are insufficient for guarding against anchor strikes, which present the deepest penetration depth among all other hazards. However, increasing the burial depth will inevitably raise costs due to a more laborious installation process, as well as the additional cable length required. Therefore, it's crucial to optimise this burial depth to reduce costs whilst also achieving adequate protection from anchor strikes. For this study the authors designed an experiment wherein a miniature anchor was pulled through sand of various densities inside a centrifuge. The maximum depth of anchor penetration was recorded for a set of scenarios, which were investigated through centrifuge tests at different gravitational levels.

The grain size of the sand was not found to be impactful, however, a direct correlation was observed between anchor size and penetration depth, leading to the development of updated guidelines for cable burial depth based on anchor mass, fluke size and ship mass. These range from a minimum of 1 m to a maximum of just over 3 m, the latter recommended for areas travelled most frequently by the largest ships. Understanding where these shipping lanes are is clearly a key concern for cable route planning. This study, along with Cao *et al.* (2021), emphasise the benefits of burial within sandy sediments. However, increased sediment mobility should be expected in sandy environments, given they typically exhibit higher energy levels compared to softer sediment environments (Coughlan *et al.*, 2021). Moore *et al.* (2021) recognise this as a limitation of their study, since migrating bedforms or scouring beneath the

cables may lead to cable exposure, even in areas where cables were buried according to their guidelines.

2.4. Site Suitability

Careful spatial planning is required to ensure the correct allocation of sites for ORE infrastructure, including SECs. Site suitability mapping is a tool utilised to identify the most appropriate locations for various developments but may also be used in environmental management or conservation efforts (Malczewski, 2006). This technique involves evaluating multiple criteria that influence the potential success, or sustainability, of a site for a specific purpose. Such criteria often include the environmental, social, economic, and physical characteristics of an area.

Site suitability mapping proves highly effective for route design purposes. In fact, some of the earliest examples of site suitability mapping were designed for just this application. In “*Design with Nature*”, McHarg (1969) popularised the application of the “overlay” methodology, wherein multiple criteria layers were combined into a single composite map (McHarg, 1969). The applications of this are numerous, with one case study geared towards road planning wherein cost levels (high, medium, and low) were assigned to various spatial criteria layers associated with road construction. The outcome was a suitability map which could be used to plan a transportation corridor, prioritising areas assigned the lowest environmental and social cost.

Geographic Information Systems (GIS) play a crucial role as tools in the field of spatial planning and site suitability analysis. Using GIS, the appropriateness of geographical areas for various factors can be assessed and visualised, aiding planners and other stakeholders. These factors encompass a broad spectrum, ranging from land-use and housing suitability (e.g. Topuz and Deniz, 2023; Can, 1992), to the development of infrastructure and renewable energy (e.g. Vasileiou *et al.*, 2017; Butschek *et al.*, 2023). Additionally, GIS can be employed to evaluate the risk posed by specific hazards across an area, such as landslide susceptibility (Basharat *et al.*, 2016), earthquake zones (Makrakis *et al.*, 2023), and flood-prone areas (Tkach and Simonovic, 1997).

Prior to evaluating the suitability of a particular region for a specific purpose within a GIS, it is crucial to identify and assess the main influencing criteria. Often, these criteria will not uniformly impact suitability. The challenge for decision-makers lies in determining the hierarchy of these factors and effectively representing these judgements on the final suitability map (Holloway, 2023). A Multi-Criteria Decision-Making Analysis (MCDA) provides a framework for assessing various criteria and factors to make informed decisions and identify

the most suitable solution to the problem at hand. Employing MCDA techniques within a GIS allows for the integration of spatial data and analysis, enabling a comprehensive evaluation of multiple criteria simultaneously. By systematically ranking these criteria, decision-makers can make informed choices and effectively address complex spatial problems, ultimately leading to more sustainable and well-informed decision-making processes.

Malczewski (2006) reviewed over 300 articles published between 1994 and 2004 concerning MCDA in GIS. The decision problems examined in each study exhibited diverse categorizations. The most prevalent among these were land suitability analysis, present in nearly 30% of the articles, followed by plan/scenario evaluation in 15.4% of the articles, site search/selection in 14.5%, and resource allocation in 11%. The study recognises the distinction between multi-attribute and multi-objective decision-making analyses. Typically, multi-attribute decision-making analyses are utilised for selection purposes, where a predefined, finite set of alternatives is presumed. Multi-objective decision-making analyses are tailored towards design considerations, where the solution lies within a range of possible outcomes. The study recognises the benefits of MCDA for supporting spatial decision-making, particularly in policy recommendations, since value judgements of the decision makers can be identified leading to a more transparent approach.

The most cited multi-attribute technique from the literature was the Weighted Summation method, wherein a set of criteria are assigned weights basing on their importance to the overall goal of the decision-making process (Malczewski, 2006). Once the weights are assigned, the individual criterion scores are multiplied by their respective weights and then summed across all criteria to obtain a “weighted sum” for each alternative. The alternative with the highest weighted sum is considered the most favourable option.

Another widely used method for determining the weights of individual criteria is the Analytical Hierarchical Process (AHP), developed by Saaty (1980). This approach involves performing a series of pairwise comparisons within a table consisting of reciprocal matrices of all the criteria being assessed. Rankings are assigned on 1-9 scale based on the relative importance of one factor compared to another, 1 being of equal importance and 9 being extreme importance (Saaty, 1987). The comparisons are quantified and processed to produce a set of priority weights, which can be used to rank the alternatives and make a well-informed decision. AHP is widely used in various sectors, including business, engineering, and government, for tasks such as resource allocation, policy analysis, and project selection.

2.5. The Analytical Hierarchical Process in GIS

Basharat *et al.* (2016) applied weights derived from AHP to evaluate nine of the key causative factors on landslides in a region of the Northwestern Himalayas in Pakistan. The criteria weights were used to combine the nine criteria layers in GIS using the Weighted Overlay Analysis tool to create a landslide susceptibility map which highlighted 15.83% of the study area as having a Very High Susceptibility to landslides. The results were validated using real world landslide occurrence data and showed a 76% correlation between this data and the susceptibility map. The resulting map highlighted existing towns and cities in landslide prone regions and identified areas of low susceptibility which would be more suitable for future construction.

In a neighbouring area of Pakistan, Hassan *et al.* (2020) employed a similar methodology to that of the Basharat *et al.* (2016), in this case creating a land-use suitability map aimed towards sustainable agriculture. The weights were assigned based on the expert opinion of the authors, which was informed by the local knowledge of residents of the study area. The study's findings indicated that only 13% of the area was highly suitable for agriculture whilst 52% was permanently unsuitable. The authors acknowledged the limitations of AHP, underscoring its vulnerability to bias, which could potentially lead to distorted outcomes.

Topuz and Deniz (2023) also utilized the AHP method to create land use suitability maps for a rural province in Turkey using eleven key factors. In this study, the suitability of the region was assessed for three distinct land-use types: forestry, meadow-pasture, and agriculture. This process necessitated ranking the eleven factors across three separate AHP tables, as the influencing criteria vary for each land-use type. Integration of these rankings using the Weighted Overlay method resulted in maps identifying areas highly suitable for each land-use category. A comparison with existing land-use patterns revealed a significant correlation between areas deemed highly suitable for forestry and the locations of existing forestry. However, the study also revealed that agriculture occupies extensive regions that would be better suited for pasture.

In summary, AHP excels in site selection exercises due to its structured and systematic approach to decision-making. The pairwise comparison method enables decision-makers to quantify subjective preferences and develop a hierarchy of multiple criteria. Additionally, decision-makers can ensure consistency in their judgments by calculating the AHP consistency ratio. AHP's capability to synthesize diverse criteria into a single overall score makes it

particularly effective for balancing multiple factors, such as environmental impact, economic feasibility, and social acceptance. Compared to other MCDA methods, AHP provides a more intuitive framework, making complex decisions more manageable and comprehensible. The method's transparency and flexibility further enhance its applicability, establishing AHP as a robust tool for optimising site selection decisions.

2.6. Site Suitability Mapping for Offshore Renewable Energy

Vasileiou *et al.* (2017) used AHP to select sites for ORE, in this case for the development of hybrid wind and wave energy systems in the Aegean and Ionian Seas surrounding Greece. As a first step, a series of exclusion criteria were developed, and the subsequent exclusion zones were removed from the study area. Subsequently, key economic, environmental and socio-political factors were identified and weighted criteria values derived from AHP were applied to a suitability map. These included wind speed, wave energy, water depth, distance to the shore, local grid connection points, population served, shipping density and distance from ports. The criteria weights were derived from the authors own expert opinion as well as from previous, similar studies. The highest ranked criteria included wind speed, wave energy and water depth.

The resulting map identified twelve sites that may prove suitable for development of this hybrid technology, ranging in size from 21-517 km². The study emphasizes the necessity for expertise in both the study area and the optimal environmental conditions suitable for deploying the currently available technology. In this case, water depths emerged as a significant controlling factor, as only a relatively small portion of the study area with a suitable wind and wave resource fell within the range of less than 500 meters depth, a threshold chosen by the authors as the upper limit for floating platform technology. The authors concluded by recommending further studies which integrate the perspectives of local stakeholders, residents and policy makers into the AHP pairwise comparison matrix to address the factor of social acceptance. They also recommended studies using alternative MCDA methodologies to compare against the results derived from AHP.

Taoufik and Fekri (2023) implemented a modified version of AHP, termed the Fuzzy Analytical Hierarchical Process, to determine site suitability for offshore wind energy development in Morocco. This approach was chosen to account for the subjectivity of the chosen values introduced during the AHP workflow. Instead of exact numbers, a range of values is assigned for each criterion and a geometric mean value is calculated. This study dealt with eight site selection criteria which, many of which were comparable to those identified by Vasileiou *et al.* (2017), but also considers distance from high density tourist areas and seabed sediment thickness. Six exclusionary criteria were also identified, which included shipping routes as well as buffer zones around known submarine cables, blue flag beaches, migratory bird routes and other protected areas.

The final composite map categorised the Moroccan offshore territory into five classes, graded from 1-5 with 1 being “Unsuitable” and 5 being “Extremely Suitable”. The authors identified three sites deemed most suitable and calculated the potential energy capacity of an offshore windfarm on each site, assuming the use of 5 MW turbines with a spacing factor of 0.794 km². They concluded that 13.3 GW of energy capacity could be installed within these extremely suitable areas.

Butschek *et al.* (2023) developed weights from AHP to assess the key technical, economic, social and environmental factors related to site selection for ORE. The study area in question was off the southwest coast of Ireland. For this study a stakeholder workshop was organised with 25 experts from academia and industry consulted. Nine key attributes were selected for pairwise comparison, these were: Wind Speed, Water Depth, Wave Height, Ocean Current, Seabed Mobility, Depth to Bedrock, Infrastructure, Biological Factors and Visibility. These geospatial layers were collated and standardised to a 1 km resolution, with evaluations on a scale ranging from 1 to 100. The study aimed to reach consensus on the weights of these criteria (i.e. the mean of the AHP values) with the goal of reducing bias. As with the previous studies discussed above, wind speed and water depth emerged as the most prominent criteria, with biological constraints – such as impacts on seabird populations and fish stocks – also ranked highly. There was, however, a significant degree of variation between some of the expert opinions. The authors decided to iteratively compute 1,000 Monte Carlo simulations using the AHP weights based on the results of the survey to account for this variability. This produced a “selection frequency map” which highlights 10% of the most and least favourable areas.

The authors conclude by recognising the drawbacks of AHP in site selection studies, namely the subjectivity of the weights which frequently stem from the expert opinion of individual authors. They note that if the results from AHP were to be truly objective, the weights derived from the panel of experts should be broadly similar. Instead, the survey results revealed considerable variation in responses regarding the importance of some of the nine attributes. For example, the importance of wave heights ranged from 1.2 – 43.6%. The study underscored the need for group consensus when applying an MCDA to geospatial analysis, particularly when competing interests are included in the same analysis.

Several studies focused on site suitability mapping for offshore renewables using the INFOMAR database have been published. Murphy *et al.* (2016) took advantage of this high-quality dataset to identify potential sites for ORE in the Irish and Celtic Sea and recommend

appropriate wind turbine foundations for each site. The study focussed on water depth (bathymetry), sediment type and sediment mobility to categorise regions within the study area according to their suitability for specific fixed-bottom wind-turbine foundations. Using INFOMAR's MBES bathymetric data, water depth and seafloor morphology were investigated. Sediment type was deduced from sediment samples, as well as the backscatter response derived from MBES data. Site specific investigations included analyses of sub-bottom profiles with the goal of determining the overall character as well as vertical and lateral extent of the main sedimentary units. INFOMAR contains a vast dataset of SBP data, however most of the data were collected via a "pinger" system which does not achieve the necessary penetration depths required for turbine foundation design. Instead, the authors focused on "sparker" data which achieves the required seafloor penetration, however it is more limited in extent in terms of availability. The authors chose to focus on foundation design since "these are the only sections of a windfarm which interact with the seabed and sub-surface sediments". While turbine foundations constitute the most significant footprint on the seafloor and penetrate deeper into the sediment (up to 50m), both intra-array cables and SECs also interact with the seabed and exhibit comparable requirements for optimal seabed conditions to foundations. Therefore, the INFOMAR SBP dataset could also be utilised for cable route design.

Guinan *et al.* (2020) studied the INFOMAR dataset and noted the necessity for an accurate characterisation of the seabed substrate for the planning and design stages of ORE, particularly in site selection and turbine foundation design, but also for cable routing. The text discusses the advancements in mapping the geological characteristics of the seafloor, emphasising the use of autonomous survey platforms and remote techniques like MBES for data collection and analysis. The paper examines two case studies, one of which covers most of the Irish Sea and a portion of the Celtic Sea, on the south coast of Ireland. Using INFOMAR bathymetry and the European Marine Observation and Data Network (EMODnet) 1:250,000 seabed substrate map, key sedimentological and geomorphological features of the study area were identified. This in turn was used to produce a constraint map, which highlights areas with limited suitability for ORE development, such as exposed bedrock, highly mobile sediments and shallow gas. Sediment mobility was linked to risks to both wind turbine foundations (through scouring) and cables due to the increased likelihood of cable exposure or free spanning when sediment waves migrate over the buried cable. The study highlights the importance of initiatives like EMODnet and INFOMAR in providing access to harmonised marine data, supporting sustainable marine

management, and contributing to the growth of maritime industries, by making marine data freely available for various sectors and policy objectives.

Arosio *et al.* (2023) produced a map of the geomorphological features of a portion of Ireland's continental shelf, at 10 m resolution to a depth of 200 m. This study utilised up to date INFOMAR data and combined morphological interpretations with semi-automated mapping techniques to produce a map which represents the upper 2 m of the seafloor. Features were reclassified based on internationally standardised terminology to align with other datasets in the EMODnet database. Thirty-five separate landform units and four substrate types were categorised, with prominent features such as paleo-valleys, glacial deposits and sediment banks identified and discussed. The study highlights the substantial amount of exposed bedrock around the southwest coast, with 30% of the mapped seabed in this area showing exposed bedrock or bedrock covered by thin, surficial sediments. The findings of the study are of particular relevance to developers and spatial planners of ORE in Ireland, given the increased cost associated with constructing infrastructure, and laying cables, on exposed bedrock.

Peters *et al.* (2020) analysed data from INFOMAR and others to create a seabed stability model for a large portion of Ireland's marine territory. This study incorporated bathymetric and geological data to create interpolated maps for sediment classification, angle of repose and critical bed shear stress. These data were used to deduce seabed stability with the final stability probability raster produced through Empirical Bayesian kriging (EBK) interpolation. The results reveal the highest probability for mobile sediments in the western Irish Sea and in parts of the shallower, near shore areas of the southwestern and northwestern Atlantic coasts. Conversely, much of the south coast and deeper regions of the Irish Sea were identified as the most stable regions. The model is limited by the fact it does not consider local currents, which are variable around Ireland and would likely lead to less stable sediments in certain settings. Nonetheless, the results provide a novel tool to guide planners of ORE around Ireland and reduce the risk to offshore infrastructure posed by mobile sediments.

2.7. Route Selection in GIS

Typically, GIS route selection tools serve navigational goals, seeking to minimize the overall distance or travel time, or to avoid specific features within a designated network of pathways, such as a road network (Holloway, 2023). However, the same process can be applied to planning a new route, for example constructing a new road, hiking trail, or a submarine cable or pipeline route. To achieve this, the known influencing criteria must be identified to create a suitability surface. The previous section covers examples of the use of an MCDA to create such a surface in a GIS.

Numerous studies in the literature have addressed the integration of site suitability analysis and route selection, with automated GIS tools streamlining the process. As would be expected, the literature on GIS based route selection largely considers route selection on land, however many of the same principles can be applied to route selection in a marine setting, provided there is sufficient data coverage of the area in question.

A recent article by Effat *et al.* (2022) combined economic, social, and environmental criteria using AHP derived weights into “cost surfaces”. A Least Cost Path Analysis (LCPA) was implemented in a GIS on these surfaces to determine options for four routing scenarios, aimed at planning a tourist route linking three archaeological sites in Egypt. The three cost surfaces, consisting of numerous spatial criteria combined into raster layers, were each biased towards different concerns. These were economic, environmental, and social with the fourth surface being an equal combination of all three. The resulting paths were then compared against a set of evaluation criteria, revealing the environment paths to be the most suitable. Since it is flexible to the specifications and requirements of a particular site or style of route, this method can be applied to range of other scenarios, including submarine cable routing.

Many published examples of GIS based submarine cable routing consider long distance, transoceanic submarine telecommunication cables, while others address the planning of intra-array cable networks that connect wind turbines and substations within OWFs. The third category of papers, which are of particular relevance to this study, pertain to SECs.

Wang *et al.* (2019) developed a cost-effective approach to the planning of an extension to an existing submarine telecommunications cable network in the northwest Pacific Ocean. This was achieved using the fast-marching method (FMM). Various design criteria were considered, including overall construction cost, water depth, slope, and sediment hardness. Criteria specific

to this region were also considered, namely earthquake zones and sites of known volcanoes. The authors developed extension paths using both the fast-marching method and Dijkstra's algorithm, the latter being the foundational algorithm behind GIS based LCPA. Both methods are similar, however FMM differs in that progress from the start point to the endpoint is achieved via a wavefront, which represents a set of points moving at equal speed across a surface. The results showed considerable cost savings associated with FMM, up to 17.5%.

Building upon their 2019 study, Wang *et al.* (2021b) developed an algorithm combining simulated annealing (SA) and FMM to provide a benchmark for planners of long distance, transoceanic submarine cable paths. The results optimise paths for minimal life-cycle cost and cable design considerations. The FMM/SA technique was found to be highly useful when compared to both real-world cable paths and other, similar algorithms, namely random restart hill climbing and Monte Carlo simulations. The results provide useful insights into the design considerations needed to plan a long-distance route in 3D space. It should be noted that while similar considerations apply to cable routes from ORE projects, these routes would typically be planned over much shorter distances than those discussed by Wang *et al.* (2019 and 2021b). Consequently, the advantages of FMM over a LCPA may not be as significant in these contexts.

Roetert *et al.* (2017) optimised the paths for intra-array cables for an OWF constructed within a morphodynamic environment i.e. an area on the seabed with mobile sediment. The process involved creating optimised paths connecting all the wind turbines to each other and an offshore substation, initially assuming a flat seabed. The algorithm employed for this solution was the Genetic algorithm which uses principles of evolution and adaptation to select the best connection route. The process begins with the generation of multiple layout solutions determined by the number of turbines present, where, for instance, forty turbines would yield eight hundred potential solutions. Weights for these solutions are derived by summing the edges within the network, as delineated by the distance matrix encompassing all feasible connections between pairs of turbines or between a turbine and the substation. Eight solutions are subsequently selected from this set, and the fitness of each is assessed. The solution characterised by the lowest weight is deemed optimal. Each individual path was then optimised in the vertical plane to account for changes in the seabed level due to sediment wave migration. This was achieved by creating a cost surface using Deltares (2016) model for predicting seabed level change in morphodynamic areas. Dijkstra's algorithm was then used in the horizontal plane to find the best or "cheapest" path for each connection. The resulting routes demonstrated predicted reductions in both cost and risk during the construction and maintenance phases of

an OWF situated in areas of mobile sediment. A similar approach could be applied to SECs routed through areas with known sediment migration patterns.

Additional research, exemplified by the work of Cazzaro and Pisinger (2022), examines the optimal configuration of intra-array cable networks in an area with known obstacles. This involves routing cables around obstacles and employing a Large Neighbourhood Search heuristic, which systematically explores different subsets of potential solutions. Both branched and radial networks were computed using the heuristic for possible windfarm layout, where numerous wind turbines were connected to a set of substations. The resulting paths showed to have comparable cost-savings to other, more time-consuming routing methods found in the literature. The study does not consider SECs, and the method may not be suitable for them. Unlike network routing, SECs follow a single pathway and may encounter a more diverse set of obstacles and mitigating criteria compared to those within the windfarm array site.

Jiang *et al.* (2019) develop a novel method of decision making, termed the fuzzy evidential reasoning approach and applied it to SEC routes from an OWF in China. The fuzzy logic approach is used to describe both quantitative and qualitative factors using “fuzzy sets”. The evidential reasoning approach is used in this study since Fuzzy Logic does not leave room for uncertainty. Evidential reasoning uses a “belief degree” and can be used in situations with incomplete information. Ten influencing criteria were identified by the authors which were grouped into four categories, summarised as routing condition (overall length and water depth), navigational environment (shipping lanes, fishing), cable reliability (seafloor sediment, seawater corrosion, distance from existing cables) and special zones (distance from nature reserves and fisheries). Three routing options from the proposed offshore windfarm were designed during a stakeholder workshop were then assessed based on the developed methodology. The route selected by this method was the same as the consensus opinion reached by the stakeholder workshop, which further strengthens the reliability and applicability of the proposed integrated approach, offering valuable insights for future offshore wind farm projects.

Makrakis *et al.* (2023) utilised GIS to create a series of routes for submarine cables crossing a seismically active region in the Eastern Mediterranean Sea. The authors present a methodology that combines an LCPA for route selection along a cost surface, defined through weights derived from AHP. Three main criteria were selected, namely slope inclination, water depth and seismic fault zones. The authors prioritised these three criteria differently in five separate scenarios, three scenarios where one criterion was given extreme importance over another, one

scenario where each were equally important, and a final scenario where the prioritisation was determined by experienced routing engineers. The routes were calculated using a support tool developed by the authors, which was built into the ArcMap GIS software, however the authors note the LCPA tool in ArcGIS Pro would provide similar results. Two sets of cable routes were designed based on real projects, one between Crete and Libya and another between Crete and Egypt, with the results of the former compared against an existing cable. Seabed substrate was not considered, and a uniform burial depth of 0.5 m was assumed for each scenario. The authors recognise this limitation and note that local sedimentary conditions could affect the suitability of an area for a cable or pipeline in a seismically active area, highlighting the need for a comprehensive database of relevant geospatial information for such studies.

Huang *et al.* (2018) designed a classified seafloor map along a cable route from images obtained using an autonomous underwater vehicle equipped with a side scan sonar. By utilising a probabilistic classifier based on a Naive Bayesian filter, the substrate type and obstacles along the route can be identified in real-time, as the data is being collected. The authors developed a probability roadmap algorithm, which involves using a probabilistic map of seafloor obstacles combined with the A* algorithm for effective and efficient route planning. The methods were tested on a pre-planned cable route between two islands in Taiwan which had a mix of muddy, sandy and rocky seafloor sediments. Once surveyed the seabed classification results were combined with considerations of overall cable length, angle of course alteration and slope to develop a route designed in an A* algorithm. The weighting of each of these criteria was designed through consultation with experts and calculated using a weighted summation. The results of both the seabed classification and the route design were validated against those chosen by experts and showed a high degree of correlation. The study demonstrates the potential of integrating real-time seabed classification with advanced route planning algorithms to enhance the precision and efficiency of subsea cable installations.

In their 2022 study, Diaz and Guedes Soares develop a route selection methodology for SECs based on a MCDA and applied their findings to an area between a proposed OWF site and the northern Spanish Coast. The authors identified the key influencing criteria through previous literature and expert opinion. These included twelve exclusion criteria, such as military areas and environmentally protected areas. Interestingly, sand and gravel were considered exclusion factors, based on the rationale that these sediments can be extracted and used as aggregates, as cited in a previous work by the same authors (Diaz and Guedes Soares, 2020). Nine routing criteria were selected, consisting of seabed slope, seabed conditions, influence in marine

species migration paths and the distance to environmentally protected areas, to aquaculture, fishing areas, offshore platforms, areas of shipping, anchorages, and recreational sites. The criteria were ranked based on the Subjective Weighting Method with the ranks the criteria in order of importance based on expert opinion. Environmental criteria were deemed as being of high significance with slope given the most significant weighting. The resulting weights were applied to cells within the study area on a 1 x 1 km grid and the optimal route was selected through the cells deemed most suitable.

The authors concluded by noting the main factors used may not be suitable for every offshore region and should be adjusted where necessary. They also highlight that social and political aspects were not focussed on in their study, emphasising the numerous and varied criteria that may be considered when planning a cable route. However, some of the exclusion criteria are debatable. For instance, the exclusion of sand and gravel seems questionable, as these sediments are the most suitable for cable burial (Cao *et al.* 2021; Moore *et al.* 2021).

2.8. Discussion

MCDAs, such as AHP, provide a structured approach for planners to identify the relevant criteria for a project and quantify the relative importance of each criterion. In the studies mentioned above, this is most often based on the expert opinion of the authors but can also be influenced by a panel of expert stakeholders. Numerous studies implement MCDAs for ORE projects and consider the environmental, economic, and social influences on site selection within a specific region of the world's oceans. Unsurprisingly, the energy resource potential is of paramount importance for the siting of an ORE project, whether it be wind, wave or tidal energy (e.g. Vasileiou *et al.*, 2017; Taoufik and Fekri, 2023; Butschek *et al.*, 2023). Regarding the suitability of sites for cables, many of the studies concerning submarine cables deem the siting of the route of secondary importance compared to the rest of the ORE infrastructure. In essence, other aspects, such as the positioning of offshore substations and land-based grid connection points, are prioritised first. Instead, the weights or suitability scores derived from the MCDA are used to evaluate previously designed routes (e.g., Jiang *et al.*; Wang *et al.*, 2021b). The straight-line distance between these two points is considered the optimal starting point (Diaz and Soares, 2022). This prioritisation is logical, considering that SECs represent only a small portion of the overall cost of a windfarm, approximately 11-14 % for the cables and installation (BVG Associates, 2019). However, given the extremely high cost of a cable failure to a wind farm, and the anticipated increase in their presence on the seabed, the suitability of a site for cables should also be included in a site assessment. Incorporating this consideration not only helps mitigate environmental risks associated with these cables but also has the potential to lower costs for an ORE project in the long term, by identifying the most economically viable offshore regions.

RQ1: How can a Multi-Criteria-Decision-Making analysis identify and prioritise the key criteria influencing the feasibility of a submarine cable route and what are the implications for site selection in the offshore energy industry?

Ireland's marine territory is roughly 10 times larger than its landmass, and this is due mainly to its extensive continental shelf (Marine Institute, 2022). As such, the water depths within the present study area of the South and West Coast areas of Ireland are relatively shallow when compared to many of the case study sites reviewed in the literature with maximum depths of 212 m. This is significant because water depth is a controlling factor in determining viability of an offshore site for an ORE project and associated submarine cables. Given that the water

depth and wind energy resource throughout much of the study area could be considered appropriate for current windfarm technologies it is important to consider additional factors. These include seabed substrate, environmentally sensitive areas, and distance to grid connection points, which can further inform site suitability and the selection cable routes, which to date have not been included in research and would represent a significant advancement on knowledge.

Cable burial is the preferred method of protection (e.g. Carter *et al.*, 2014; BVG Associates, 2019; ICPC, 2021); however, the composition of the seabed, i.e. sediment type, and recommended burial depth varies within the literature. Diaz and Soares (2022) consider sand and gravel an exclusion factor, whilst Cao *et al.* (2021) and Moore *et al.* (2021) recommend burial within sandy sediments due to more favourable thermal conductivity properties and lower penetration depths by anchors or fishing gear within these sediments. In general, the literature recommends burial depths be assessed on a case-by-case basis, as the risks to cables are variable and may be unique to specific environments (Carbon Trust, 2015). However, in studies that consider the main risks to cables, anchor strikes, a minimum of 1 m burial is recommended (Moore *et al.* 2021). Exposed bedrock is considered a mitigating factor, due to the additional cost of protecting the cable and the environmental impact of introducing foreign material into the ecosystem (BERR, 2008).

The actual costs of submarine cables are variable, with a 2016 paper by Nieradzinska *et al.* referencing pricing of £1 million per kilometre (M/km) for 33 kV intra-array cables and £2.5 M/km for 275 kV export cables, inclusive of installation costs (Nieradzinska *et al.*, 2016). BVG Associates (2023) provide an estimate of £1.33 M/km for a 220 kV SECs with an additional £0.33 M/km for installation costs (BVG Associates, 2023). The European Union Agency for the Cooperation of Energy Regulators (ACER) published a series of cost indicators for energy infrastructure in 2023. The report states mean costs of €3.3 M/km for an offshore transmission cable based on 7 assets analysed that were deployed between 2015-2020, with voltage levels of 150 – 320 kV (ACER, 2023). It is not stated in this report whether installation costs are included in this figure, although it could be assumed so given the comparison with the other studies. Costs of cables installed on land are similarly high, ranging from €0.4 M/km to €4.4 M/km for 220 kV cables, with the highest costs associated with 2 circuit cables installed underground (ACER, 2023). Given these high costs, reducing the length of the cables both offshore and onshore is of primary importance to the economic feasibility of a cable route. As

such, the regions offshore which are within the closest proximity to suitable grid connection points will be considered the most suitable.

RQ2: Where are the regions on the seabed within the study area deemed most suitable for submarine cables from RQ1, and how will the results vary based on economic vs environmental considerations?

It is standard practice for cable routes to be designed manually on a case-by-case basis by a qualified engineer, which starts with an extensive desktop study considering all the environmental conditions and potential hazards within an area (ICPC, 2015). One or more survey corridors are then suggested for additional hydrographic, geotechnical and geophysical surveying (ICPC, 2015). The locations of the initial survey corridors are primarily determined by the placement of the offshore infrastructure and potential onshore grid connection points. Determining suitable landfall sites may involve multiple site visits. Taken as a whole, this initial process is both costly and time-consuming.

GIS-based route selection tools, such as LCPA, can streamline this decision-making process, offering planners and developers of ORE projects valuable insights into key areas. These tools can optimise route selection by considering factors like reducing overall length and installation costs, minimising environmental impact, and maximising cable lifespan and energy transmission efficiency. By running these tools in multiple scenarios (e.g. Makrakis *et al.*, 2023), the results can be assessed to inform site selection for offshore infrastructure, such as substations. This is particularly applicable in areas such as those identified by the Irish Government in the 2023 publication of the second Offshore Renewable Energy Development Plan (ORED II) (DECC, 2023b). These broad areas of interest offer numerous site options, and narrowing the focus to identify the most suitable locations for cable routes can provide valuable insights when finalising the locations for Ireland's future offshore wind farm projects.

RQ3: How can Geographic Information Systems (GIS)-based tools for route selection inform the selection of sites for cable routes, offshore substations, and cable landfall points? Furthermore, what practical implications do these tools hold for improving the efficiency and effectiveness of offshore wind farm development projects?

The literature indicates that understanding the thickness of the seabed sediment along a cable route is critical in determining the appropriate burial depth. Geotechnical sampling is recommended along a cable route in all areas where burial is recommended, however these methods are costly and time-consuming. To achieve full coverage along a route, SBP data is

required (ICPC, 2020). Seabed mapping of the current study area indicates significant outcroppings of exposed bedrock, particularly in the nearshore regions surrounding the southwest (Arosio *et al.*, 2023). This area has a considerable amount of available SBP data collected by INFOMAR, mostly collected by a ‘pinger’ system. Some studies have made use of this dataset to analyse submerged landscapes and glacial features (e.g. Tóth *et al.*, 2019; O’Toole *et al.*, 2020). To date few, if any, published studies have examined this dataset to conduct a sediment thickness analysis for ORE development. Of the studies that do examine INFOMAR SBP data (e.g. Murphy *et al.*, 2016) pinger data was mostly overlooked due to the insufficient penetration depths and was largely used for validation of interpretations from ‘sparker’ data. However, the penetration depths of the pinger data are adequate for a cable burial assessment, indicating a gap in the literature in that could be addressed through processing and interpretation of this openly available dataset.

RQ4: How can the integration of sub-bottom profile data further optimise cable routes and cable protection strategies in the South Coast DMAP, and what are the implications for cost and risk management in offshore wind farm development?

3. Methodology

This chapter outlines the methodology used within this research project, detailing the data sources and the rationale behind the inclusion of each criterion layer. Following this, the data processing methods are described, as well as the multi-criteria decision-making analysis (MCDA) used to weight each layer. The automated route selection tools employed in the study are also discussed. Finally, the chapter outlines the approach taken for selecting and processing the INFOMAR (2021) sub-bottom profile (SBP) data.

3.1. Study Area

The area chosen for this study has been selected from the Irish Government's Offshore Renewable Energy Development Plan (OREDPA) which subdivides regions of Ireland's maritime territory into six Assessment Zones, as shown below in Figure 3.1: Zone 1) East Coast – North, Zone 2) East Coast – South, Zone 3) South Coast, Zone 4) West Coast South, Zone 5) West Coast and Zone 6) West-Coast North (DCCAE, 2014). The outer limit of these zones extends to either the borders of Ireland's Economic Exclusive Zone (EEZ), the edge of the continental shelf, or 200 km from the coastline (DCCAE, 2014).



Figure 3.1: OREDP Assessment Zones, DCCAE (2014)

This project is concerned with Assessment Zones 3, 4 and 5 and has been termed the South and West Coast for the purposes of this study (see Figure 3.2 below). There has been a high degree of interest in developing OWFs in this area in recent years, with both fixed and floating offshore wind turbine technologies being proposed. The outline of the study area has been modified slightly from the OREDP Assessment Zones to provide a more accurate representation of the coastline. This covers an area of approximately 64,400 km², comprising 15% of Ireland's Maritime EEZ and lies within the North Celtic Sea and Northeastern Atlantic Ocean.

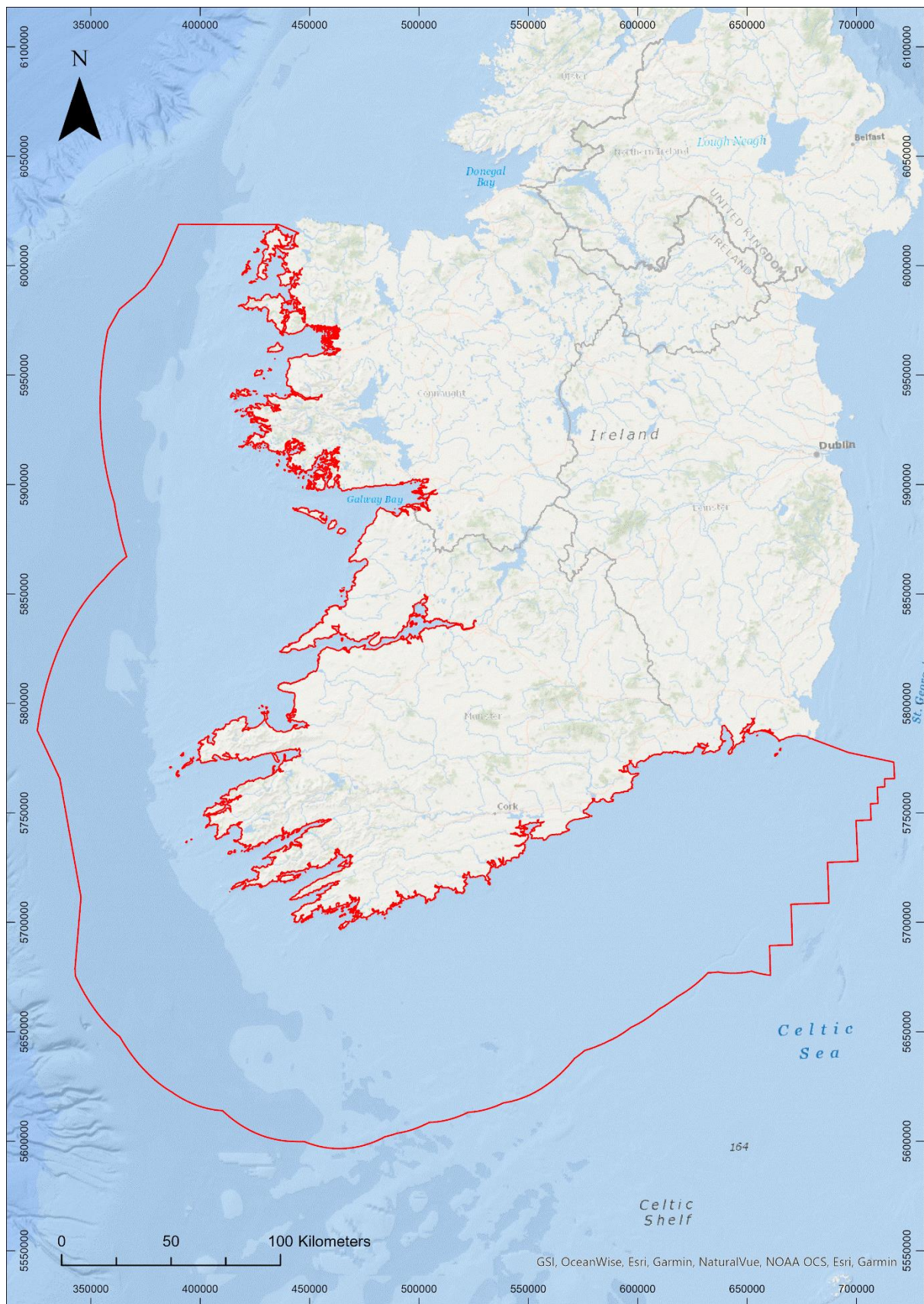


Figure 3.2: Study Area - South and West Coast

3.2. Data Collection

For this research project, a comprehensive geospatial repository of publicly available data relevant to both offshore wind energy development and cable route feasibility has been compiled. The rationale for the criteria selected for this study is grounded in the published literature (see Table 3.1 below) and tailored to the Irish context.

Table 3.1: Criteria Affecting the Feasibility of Submarine Cables as Identified in Existing Literature

Authors	Study Area	Type	Water Depth	Slope	Cable Length	Geological Hazards - Faults/volcanos/obstacles	Seabed substrate	Anchorage	Existing Cables and Pipelines	Environmentally Protected Areas	Fisheries	Military Exclusion Zones	Shipping Lanes	Shipwrecks	Angle of Course Alteration	Seawater Corrosion	Distance to population centres	Marine Species Migration Paths	Distance to recreational Sites	ORE Potential
Ardelean and Minnebo, 2023	Global	Power Cable / Interconnector	✓		✓												✓			✓
Diaz and Guedes Soares, 2022	Northern Spain	SEC from OWF	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓				✓	✓	
Huang <i>et al.</i> , 2018	Taiwan	Unspecified	✓	✓	✓	✓	✓								✓					
Jiang <i>et al.</i> , 2019	East China Sea	SEC from OWF	✓		✓		✓	✓	✓	✓	✓		✓			✓				
Kang and Lee, 2017	Not specified	Pipeline	✓	✓																
Makrakis <i>et al.</i> , 2023	Eastern Mediterranean	Power Cable / Interconnector	✓	✓		✓														
Wang <i>et al.</i> , 2019	Global	Telecommunications	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓								

Of the eighteen criteria identified from the studies listed in Table 3.1 above, water depth, slope, cable length, geological hazards and seabed substrate were the most frequently cited factors. Of these, only water depth was considered in each of the seven studies. Ten of the listed criteria are included within this study (highlighted in yellow in Table 3.1), with the remaining eight found to be not relevant to the South and West Coast of Ireland. For example, geological hazards such as seismic fault zones and submarine volcanoes are important to consider when planning a cable route, however no such hazards exist within the study area. Some criteria, such as ORE potential and distance to population centres are not explicitly considered. However, the analysis is focused on the areas designated for offshore wind development by the Government of Ireland, with the assumption that these areas contain an adequate wind resource and are suitably located near population centres.

The compiled dataset for this study includes information related to the physical properties of the seabed, such as water depth, substrate type and geomorphology. The distance to the existing electricity grid infrastructure is also analysed. Exclusionary factors were also considered, such as environmentally sensitive areas, busy shipping routes, military exclusion zones and culturally significant sites.

A significant portion of the dataset is sourced from Ireland's seabed mapping programme; the Integrated Mapping for the Sustainable Development of Ireland's Marine Resource (INFOMAR). INFOMAR is a joint venture between the Geological Survey Ireland (GSI) and the Marine Institute. This programme was launched in 2006 following on from the Irish National Seabed Survey and aims to map Ireland's entire offshore area by 2026 (Guinan *et al.*, 2020). A robust dataset is openly accessible, containing MBES bathymetry and backscatter data, along with sub-bottom profile, magnetometry and LiDAR data. The data was collected in accordance with the International Hydrographic Association (IHO) S-44 survey standards. Bathymetric data met the specifications of IHO S-44 Order 1A for depths up to 100 meters and Order 2 for depths surpassing 100 meters (Arosio *et al.*, 2023).

Another major source of data for this project is the European Marine Observation and Data Network (EMODnet), an initiative spearheaded by the European Union. Since its establishment in 2009, EMODnet has been dedicated to gathering and processing marine data sourced from multiple organizations, while also setting standards across various marine disciplines (Martín Míguez *et al.*, 2019).

3.3. Criteria Layers

Based on a review of the literature and guidelines of industrial best practices concerning the optimal conditions for SECs, several key influencing, and exclusionary, criteria were identified (Table 3.1). The following sections detail these criteria, which were chosen to assess SEC route suitability in the South and West Coast of Ireland.

3.3.1. Bathymetry

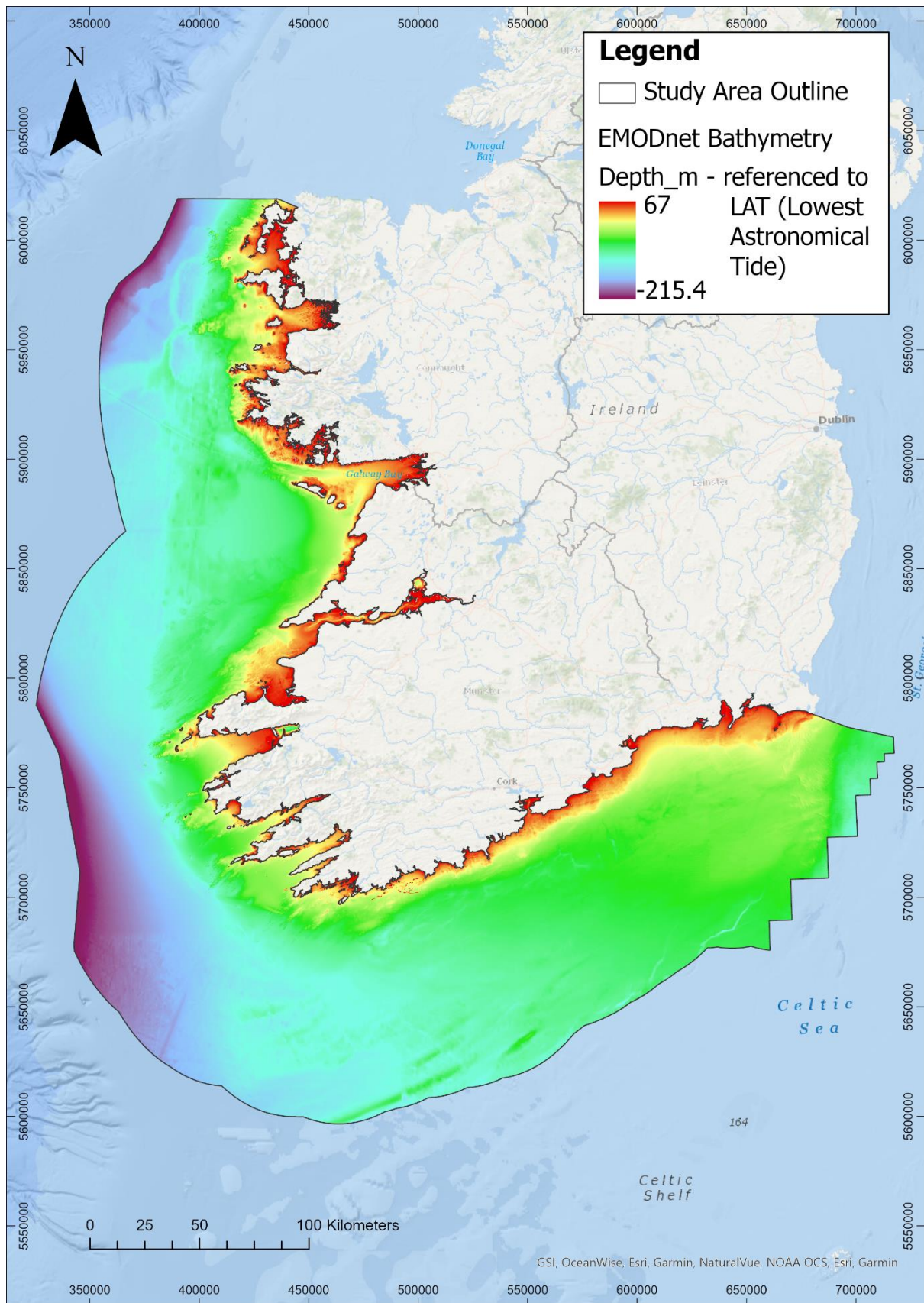


Figure 3.3: South and West Coast Bathymetry (EMODnet, 2022b)

Bathymetry is the measure of the water depth. In the same way elevation is used to study the terrain on land, bathymetry is used to analyse the topography of seafloor (Wölfl *et al.*, 2019). Water depth is critical in determining the economic feasibility of a submarine cable route, with increased installation and maintenance costs associated with deeper waters (Ardelean and Minnebo, 2023).

The bathymetric data used in this study were obtained from EMODnet (EMODnet, 2022b), using bathymetric digital terrain model (DTM) grids D3, E3 and E4 for full coverage of the study area. These depth measurements, for the portions of the grids within Ireland's marine territory, are derived primarily from the *in-situ* readings conducted by INFOMAR, acquired primarily through MBES surveys (Guinan *et al.*, 2020). Gaps in the INFOMAR dataset, due to incomplete coverage, are filled using the GEBCO 2022 Grid (EMODnet, 2022a). This model offers a global surface for the Earth, covering both oceans and land. The data is aggregated from numerous sources with measurements from both direct and indirect sources. In this instance, the bathymetric data for the areas not covered by INFOMAR is an interpolated estimation guided by satellite-derived gravity data (GEBCO, 2022).

The depth readings within the grid represent the mean depth to the seafloor measured from the lowest astronomical tide (LAT) (GEBCO, 2022). The grid is displayed in World Geodetic System 84 (WGS 84), with cell sizes of 1/16 arc minutes, which translates to approximately 115 m (GEBCO, 2022). The grid has been reprojected to Universal Transverse Mercator Zone 29N (UTM 29N) which is the coordinate reference system used for this project.

3.3.2. Slope

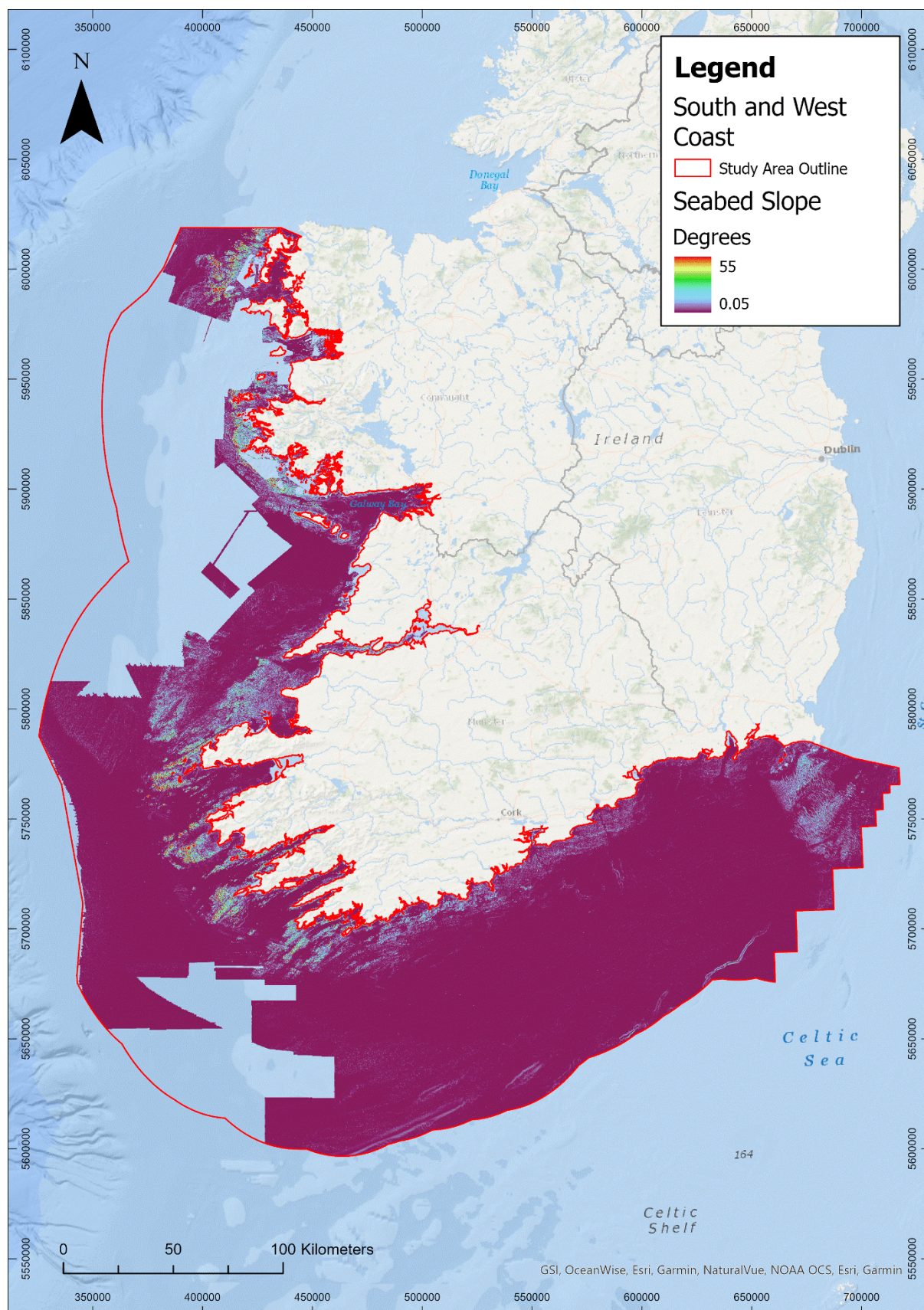


Figure 3.4: South and West Coast Seabed Slope, derived from INFOMAR (2023a)

The slope is the measure of the steepness of the seabed, which is an important consideration when designing a cable route. Local variations in slope can pose challenges during cable installation and there is an increased risk of free spanning in these areas (Diaz and Guedes Soares, 2022). Additionally, areas of higher slope may experience greater sediment instability, though this also depends on the angle of repose, which is largely determined by the sediment type (Peters *et al.*, 2020).

The slope of the study area was derived from the INFOMAR bathymetry dataset. This was chosen due to its enhanced resolution when compared to the EMODnet dataset. The areas not yet covered by INFOMAR were assumed to have a negligible slope. The slope value is calculated by the difference in depth between neighbouring cells within the bathymetric grid. This was achieved using the Surface Parameters tool in ArcGIS Pro, wherein a quadratic surface is fitted to neighbouring cells using the Least Squares Method, with a neighbourhood distance defined at 100 m (Esri, 2024).

3.3.3. Substrate

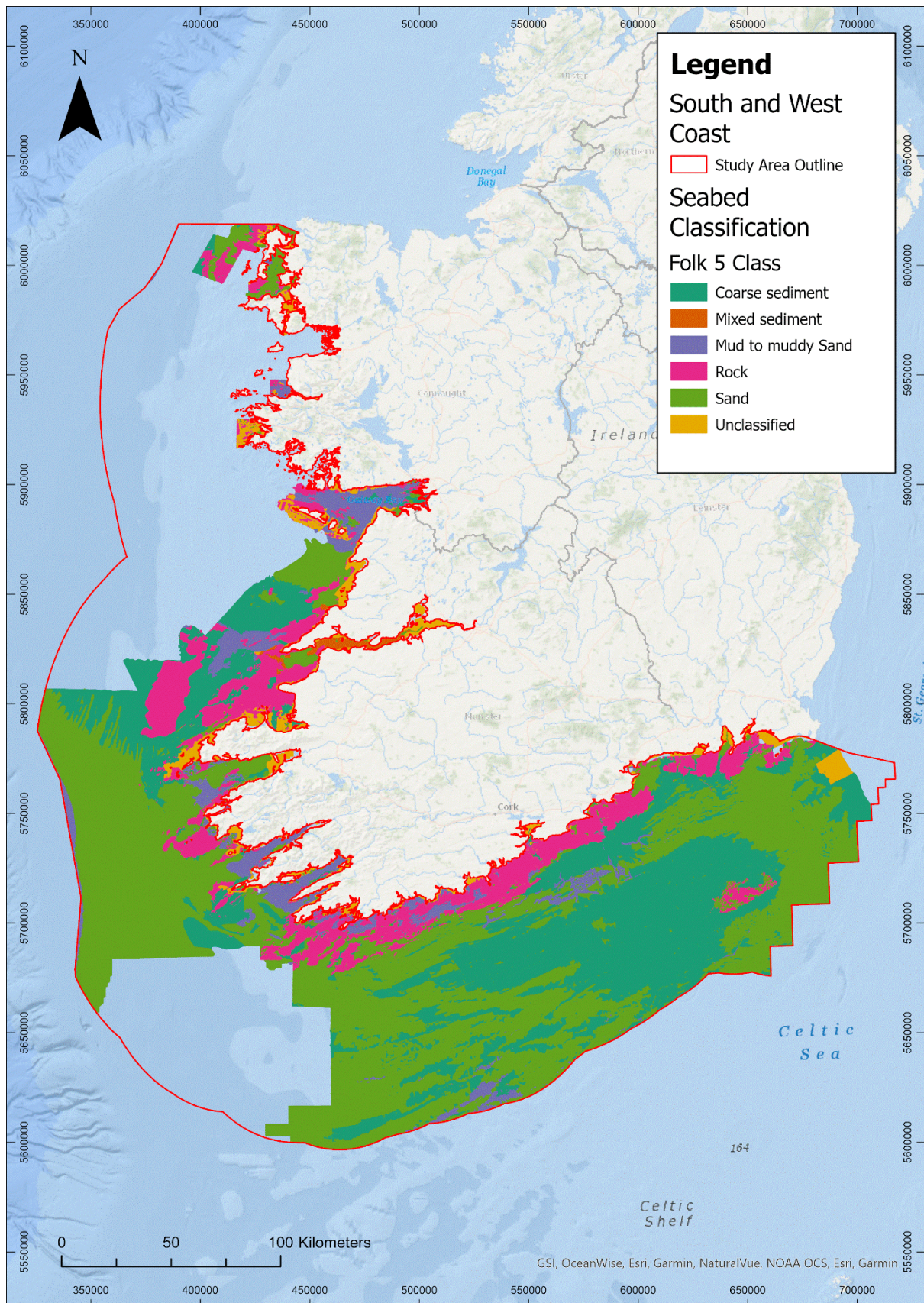


Figure 3.5: South and West Coast Seabed Classification Map (INFOMAR, 2023c)

Understanding the seabed composition is essential when designing ORE infrastructure. The geotechnical properties of different sediment types influence the choice of infrastructure and highlight potential challenges and hazards (Guinan *et al.*, 2020). This is particularly crucial for wind turbine foundation design, which can be broadly grouped into two categories: fixed and floating. Fixed bottom wind turbines are static and are placed within the seabed sediment to depths of up to 50 m below the seabed surface, generally in water depths not exceeding 60 m (Murphy *et al.*, 2016). Floating wind turbines are designed to be deployed in deeper waters, up to 1000 m, and are attached to the seabed via a system of anchors and mooring lines (Murphy *et al.*, 2016). For foundation design, generally dense sands and silts are the preferred sediment type, although gravel is often suitable (Coughlan, 2015). The substrate type is also key for planning cable routes, with cables buried where possible within the seabed to depths of 1 - 4 m (BVG Associates, 2019). More permeable, sandy sediments are deemed most suitable for SECs, with greater heat dissipation and shallower penetration depths in these substrates (Cao *et al.*, 2021; Moore *et al.*, 2021).

The seabed substrate map used within this study was adapted from the INFOMAR sediment classification map. This map segments regions of the Ireland's seabed into five broad categories, using the Folk sediment classification system (see Figure 3.6 below). These classes are Bedrock, Coarse sediment, Sand, Mixed Sediment and Mud to Muddy Sand.

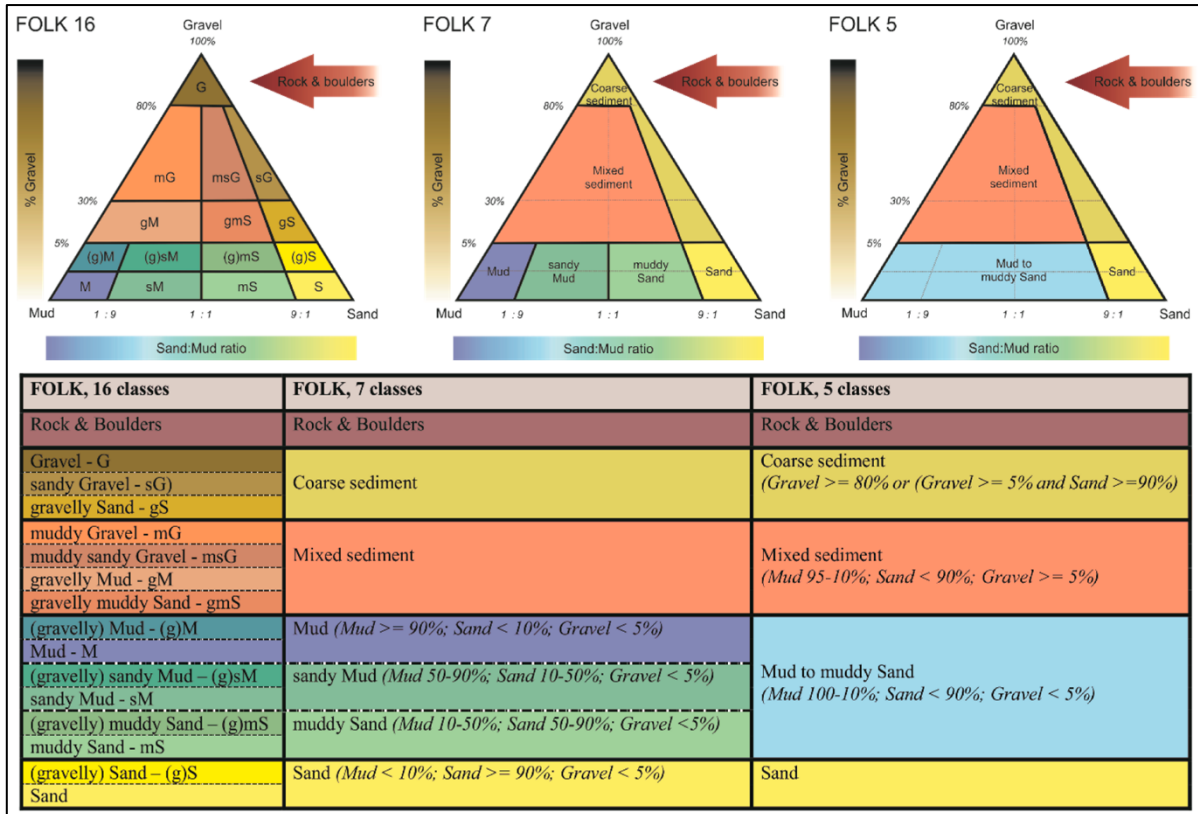


Figure 3.6: Folk Sediment Classification Scheme (Kaskela et al., 2019)

The data for this map is derived largely from MBES data acquired in numerous INFOMAR surveys. The backscatter response of the MBES acoustic signal is utilised to categorise regions of the seabed which have similar backscatter properties (Fonseca *et al.*, 2009). These properties can provide insights into the seabed characteristics, such as substrate type or habitat (Fonseca *et al.*, 2009). Ground truthing of the classification interpretations was achieved by comparison with sediment samples taken during INFOMAR surveys, generally via grab sampling techniques (INFOMAR, 2023d).

Additional substrate data was incorporated from the Irish Shelf Seabed Geomorphological Map (ISSGM_v2023) completed by Arosio *et al.* (2023), discussed in Section 2.6. This dataset was chosen due to the enhanced detail of outcropping bedrock, termed “Solid Earth” by the authors.

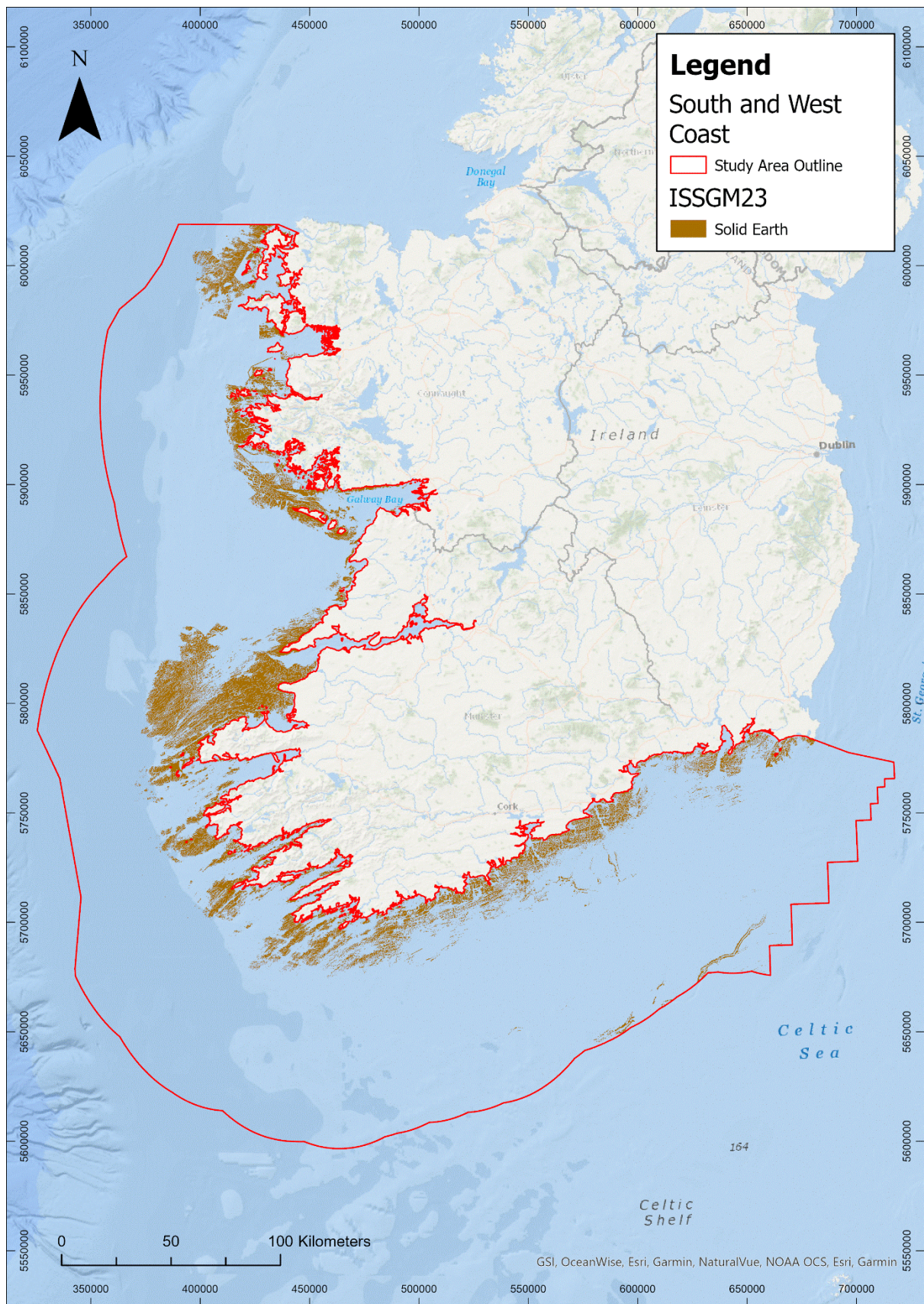


Figure 3.7: South and West Coast Exposed Bedrock (Arosio et al., 2023)

It should be noted that sediment mobility can be a risk factor for submarine cables. Migrating sandwaves, which form through vertical circulation within the water column, may induce scouring underneath cables which may lead to exposure and free spanning (Roetert *et al.*, 2017). Alternatively, excessive burial of a cable may occur through the same process, leading to overheating of the cable (Roetert *et al.*, 2017). Numerous studies have looked at the effects of sediment mobility on ORE infrastructure, particularly in the North Sea (e.g. Games and Gordon, 2014; Margalit, 2017; Roetert *et al.*, 2017) and the Irish Sea (e.g. Kenyon and Cooper, 2005; Peters *et al.*, 2020; Coughlan *et al.*, 2021) due to the high level of offshore wind development in these regions. Due to hydrodynamic forcing on the seabed from tidal currents, sediments in the Irish Sea are mobilised 35% of the time (Coughlan *et al.*, 2021). However, the same cannot be said for much of the South and West Coasts, which are dominated by storm induced surge currents (Kenyon and Cooper, 2005). Mobility rates are much lower in this area and large portion of the South and West Coasts can be considered relatively immobile (Peters *et al.*, 2020). For this reason, sediment mobility has not been chosen as a criterion within this study.

3.3.4. Distance to Grid

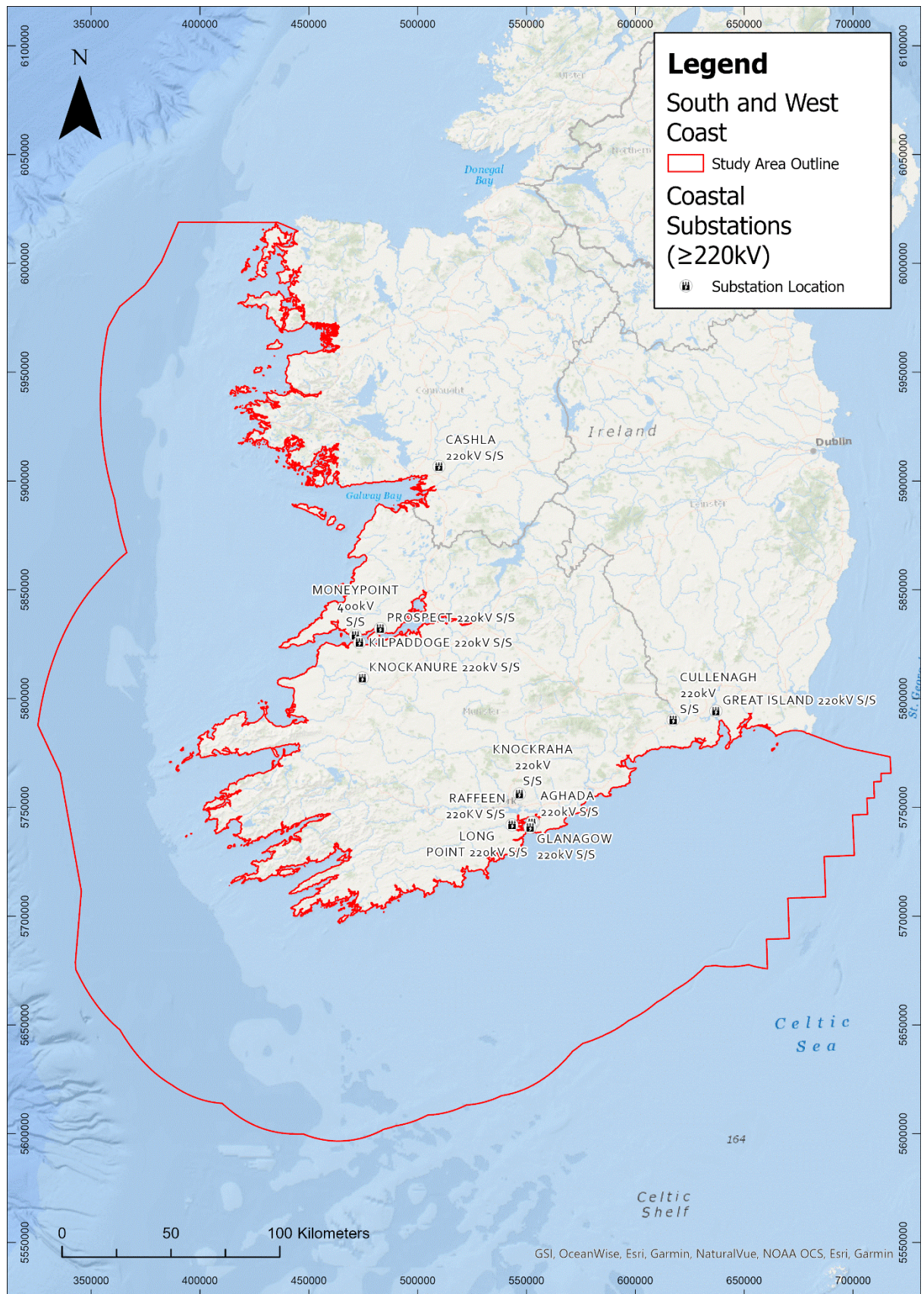


Figure 3.8: South and West Coast Coastal Substations ($\geq 220\text{ kV}$) (EirGrid, 2023c)

The main factor controlling the overall cost of SECs from OWFs is the total length of the cable itself. Therefore, minimising the distance from the wind farm to a suitable onshore grid connection point will help reduce costs (Coughlan, 2015). The earliest OWFs, constructed between 1991 and 2001, were located 0.03 – 10.3 km from the shore (Rodrigues *et al.*, 2015). Since then, OWFs have been trending towards deeper waters further from the coastline (Igwemezie *et al.*, 2019). At the time of writing, the largest OWF in the world, the Dogger Bank Windfarm in the North Sea, is also the furthest from the coast, being 144 km from the UK coastline at its closest point (Nieradzinska *et al.*, 2016). OWFs located further out to sea benefit from higher and more consistent wind speeds, and the reduced visual impact from the shoreline is also considered advantageous (Rodrigues *et al.*, 2015).

Globally, SECs from OWFs are increasing in both length and voltage (Rodrigues *et al.*, 2015). High Voltage Alternating Current (HVAC) cables at a voltage of 220 kV are becoming the standard for OWFs (BVG Associates, 2019). The process of increasing the voltage via a transformer is easier and cheaper for HVAC than High-Voltage Direct Current (HVDC) systems, which makes them the technology of choice for most OWFs currently installed worldwide (Kontos *et al.*, 2014). However, HVAC systems require addition reactive power production, and have larger power losses, both of which increase as a function of overall cable length (Teixeira Pinto and Bauer, 2011). Where distances between substations are greater than 50 km, the benefits of HVAC over HVDC systems start to decline (Teixeira Pinto and Bauer, 2011). At distances of more than 100 km, HVDC systems are recommended (BVG Associates, 2019).

Several projects which were successful in the first phase of the Offshore Renewable Energy Support Scheme (ORESS I) in Ireland have reported plans to utilise this cable technology, namely the North Irish Sea Array (Statkraft, 2024), the Dublin Array (SLR, GoBE and RWE, 2020) and the Codling Wind Park (TOBIN, 2021). As such, for the purposes of this study, only 220 kV HVAC systems are considered. Electricity substations of this voltage (or higher) within 20 km of the coastline were identified from EirGrid's electricity Transmission System Map (EirGrid, 2023c).

3.3.5. Vessel Density

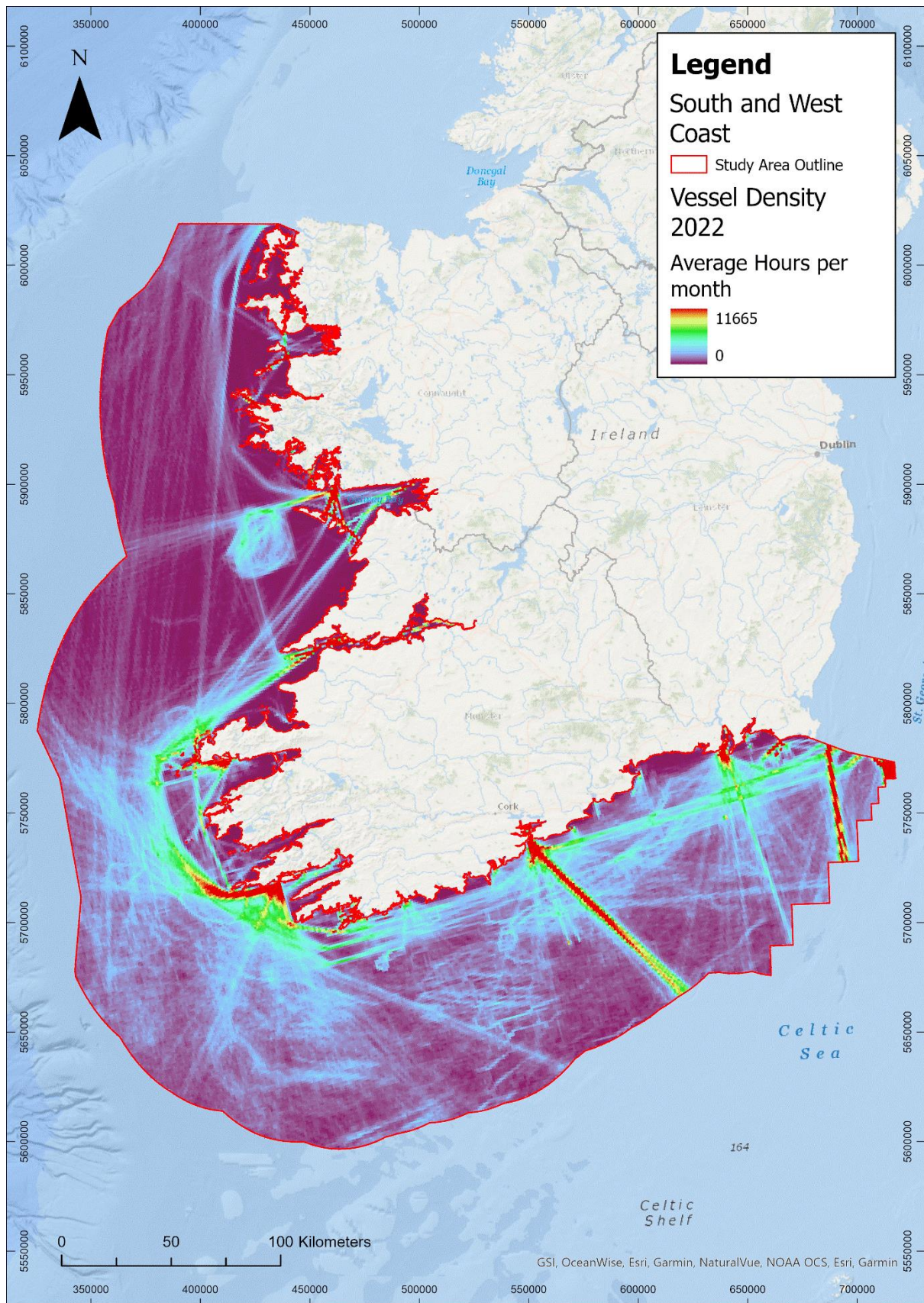


Figure 3.9: South and West Coast Average Vessel Density (EMODnet, 2022d)

To date, most submarine cable faults have been caused by human activities at sea, primarily fishing and shipping (ICPC, 2021). Consequently, identifying offshore areas where these activities are most likely to take place is essential for assessing the suitability of a cable route. According to EU Council Regulation (EC) No 1224/2009, all marine vessels greater than 15 m in length are required to have an Automatic Identification System (AIS) on board, tracking their location (EC, 2009). Detailed AIS data is not openly available, however EMODnet has a series of Route and Vessel Density maps derived from AIS data purchased from Collecte Localisation Satellites and ORBCOMM (EMODnet, 2019). The Vessel Density maps are gridded at a 1 x 1 km resolution, with each cell representing the number of hours per month spent by any vessel within that one-kilometre square area (EMODnet, 2022d). The data used for this project encompasses the annual averages for each cell in 2022.

3.3.6. Protected Sites and Exclusion Zones

When siting any ORE infrastructure, care must be taken to mitigate against harm to protected areas and to avoid designated exclusion zones. Numerous such sites exist within the study area, consisting of areas deemed environmentally sensitive, potentially hazardous, or culturally significant. Official exclusion zones also exist, and several areas have been identified within this study that may pose challenges for SEC routes.

3.4.6.1 Existing Cables or Pipelines

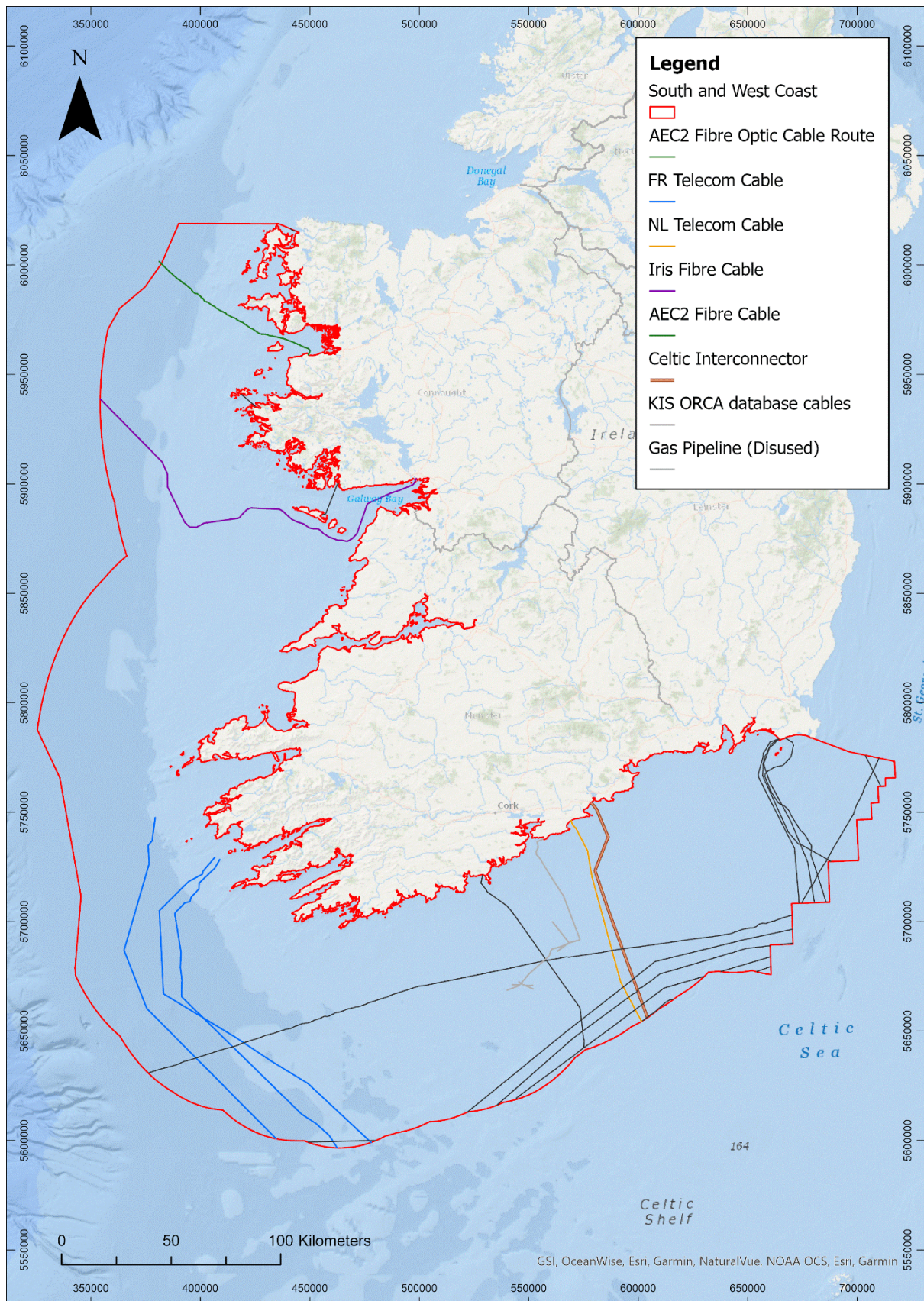


Figure 3.10: South and West Coast Cables and Pipelines

Although not officially designated as protected sites, the location of existing submarine cables or pipelines in the seabed is noted in this study as a mitigating factor for cable route suitability. Maintaining adequate spacing between existing cables or pipelines can help prevent multiple cables from being damaged by a single event (Wang *et al.*, 2019). The ICPC recommends a “working zone” 500 m either side of a submarine cable, for maintenance and repair activities (ICPC, 2013). Depending on their orientation, crossing an existing cable or pipeline may be necessary, requiring additional protection measures and incurring extra costs.

The locations of these cables and pipelines were sourced primarily from EMODnet and KIS-ORCA. The latter is a project managed by Kingfisher Information Service of Seafish, aimed at providing spatial information to the fishing industry on the locations of submarine cables and offshore infrastructure within European waters (KIS-ORCA, 2023). The locations of two, more recently installed, subsea fibre optic cables, the Iris and AEC-2 cables, were sourced from company websites and foreshore licence maps (Orrason, 2022; DECC, 2020).

The Celtic Interconnector, a HVDC submarine cable connecting the electricity grids between Ireland and France, is an ongoing project, with a portion of the total 575 km route located within the study area (EirGrid, 2020). The precise location of this cable route is being finalised, however an approximate location was digitised from a registered map sourced from the Celtic Interconnector website (EirGrid, 2020).

3.4.6.2 Natura 2000 Sites

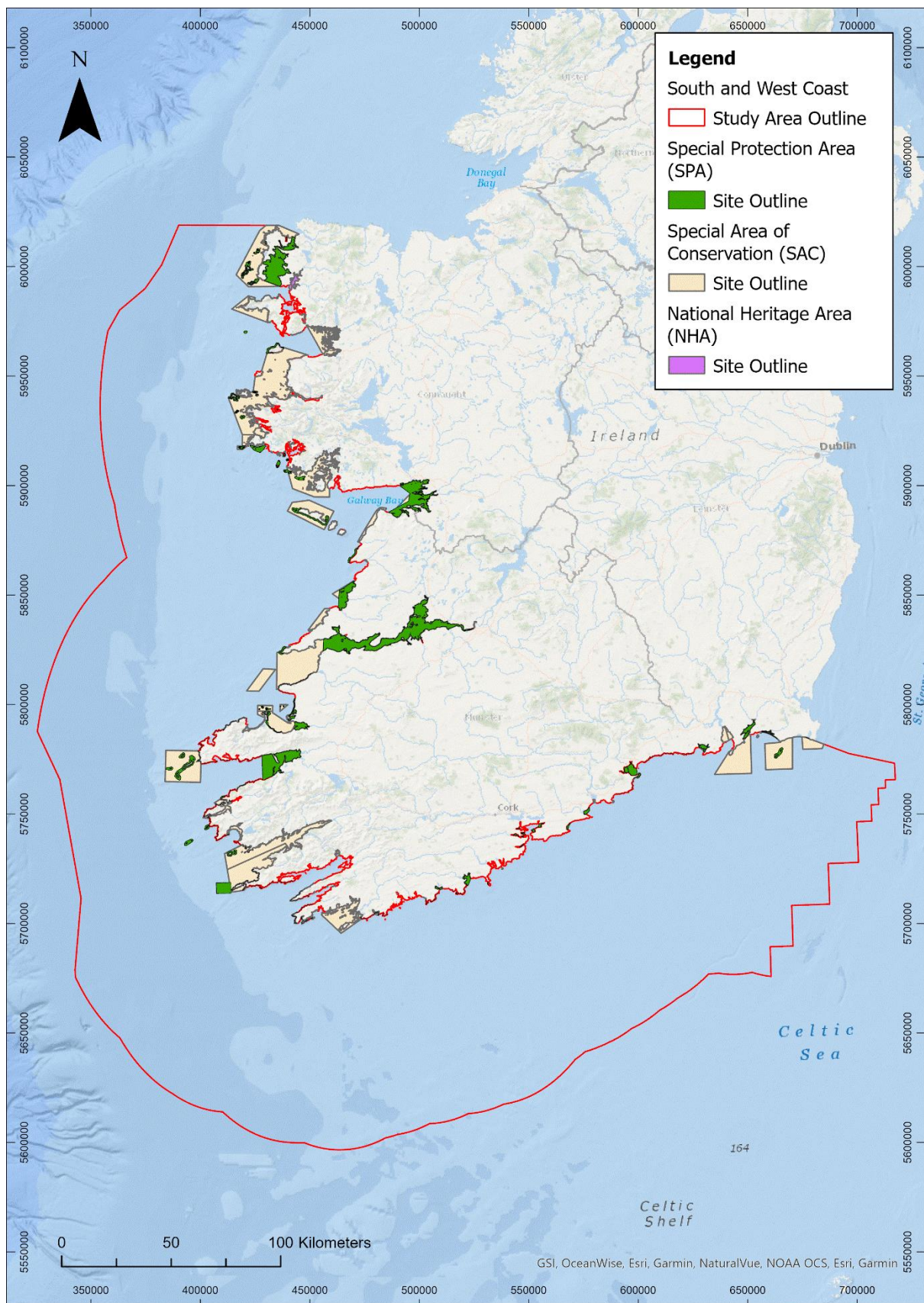


Figure 3.11: South and West Coast Natura 2000 Sites. (NPWS, 2019; 2023a; 2023b)

Natura 2000 sites are designated areas aimed at conserving and safeguarding habitats and species of European significance. In Ireland, such sites are designated by the National Parks and Wildlife Service (NPWS) and are categorised as Special Areas of Conservation (SACs), Special Protection Areas (SPAs) and Natural Heritage Areas (NHAs). SACs are areas identified as being of primary importance to protected species. The coastal and marine SACs within the study area may be assigned protected status for several reasons, such as due to the presence of Grey Seal or Harbour Porpoise populations, or vegetated sea cliff or reef habitats which are important sites for biodiversity (NPWS, 2023a). Coastal SPAs are designated based on the presence of nesting sites or breeding grounds for protected sea bird species, such as the Puffin, Kittiwake or Razorbill (NPWS, 2023b). NHAs are habitats which host protected species of plants and animals and are mostly commonly raised bogs or blanket bogs (NPWS, 2019). The NPWS is continually updating Natura 2000 sites. The boundaries for the protected sites used in this study are based on those designated at the end of 2023.

3.4.6.3 Aquaculture Sites

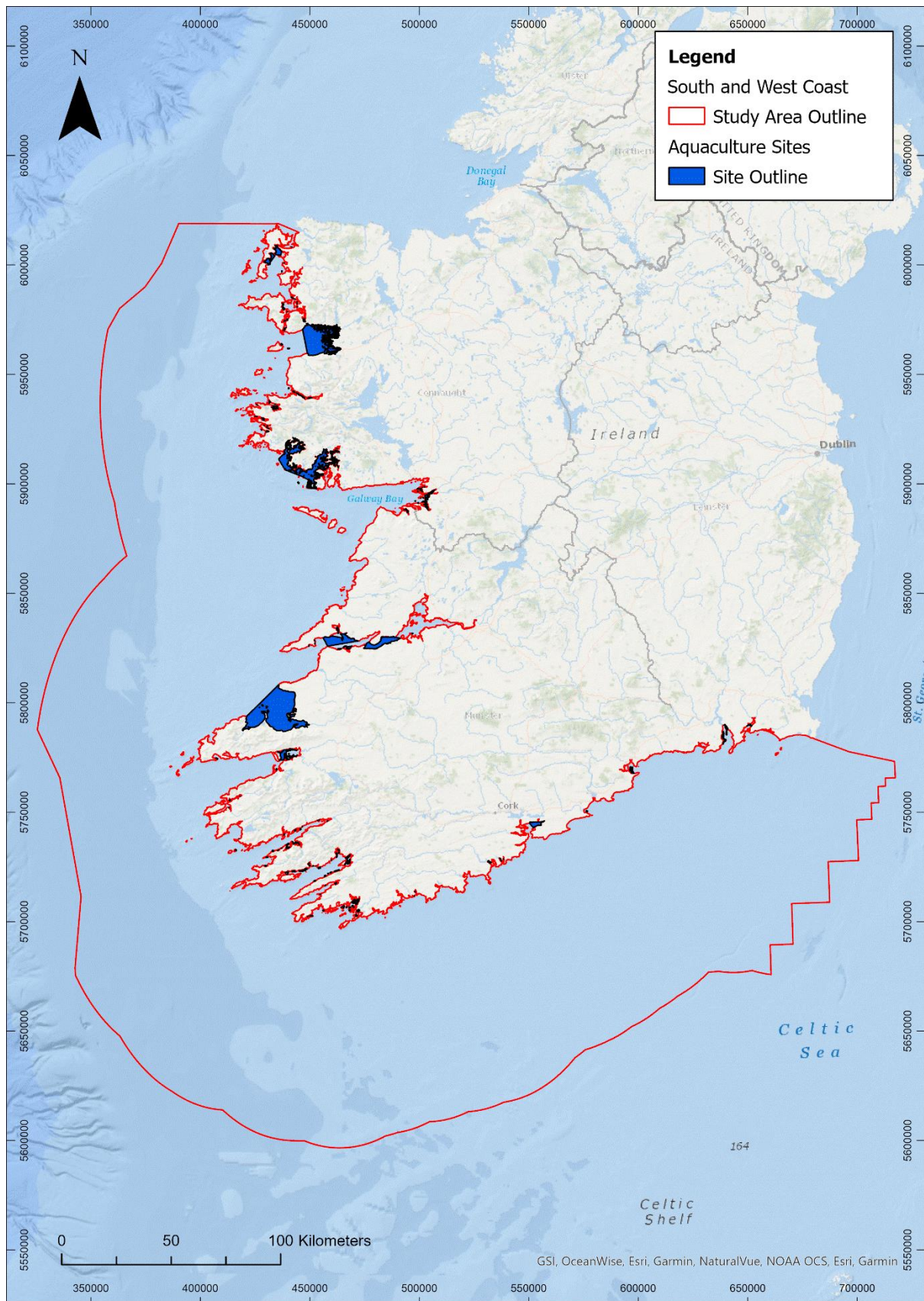


Figure 3.12: South and West Coast Aquaculture Sites (Department of Agriculture, Food and the Marine, 2018)

Several aquaculture sites exist within the study area. These are sites where the cultivation of aquatic organisms for food or other purposes is licensed. They are predominantly situated in foreshore marine environments within bays and estuaries. Shellfish, such as oysters and mussels, are the most produced species within these zones. Given the feeding mechanisms of these organisms, the possibility of suspended sediments formed during cable installation may interfere with production (BERR, 2008). As such, avoidance of these zones is recommended.

3.4.6.4 Offshore Dump Sites

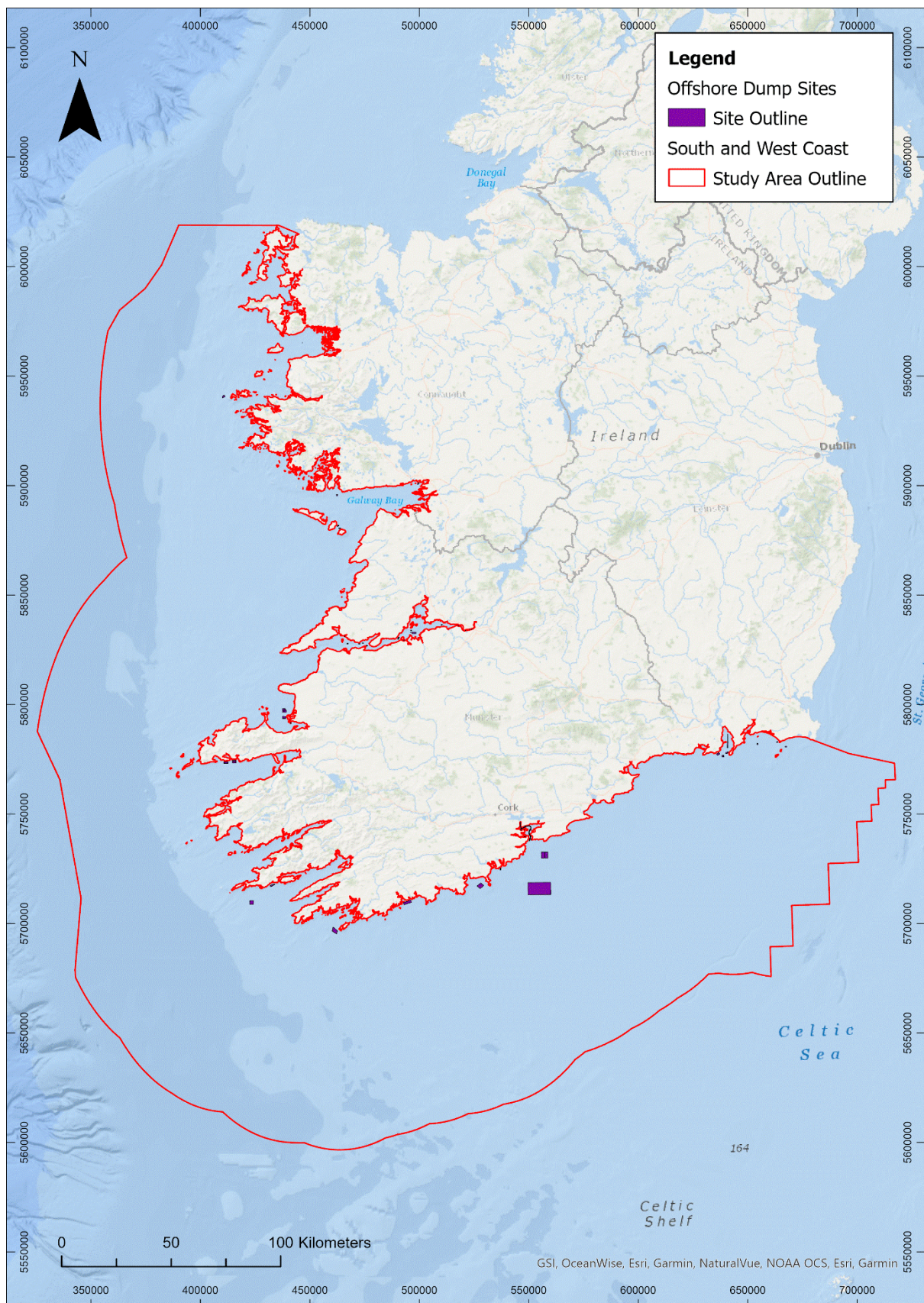


Figure 3.13: South and West Coast Offshore Dump Sites - Active and Inactive (EPA, 2023)

Some of Ireland's most important ports exist around the South and West Coast. These require occasional dredging to maintain adequate water depths within the port, which can change over time through natural sedimentation processes. This material is removed and may be dumped at sea at a designated offshore dump site. Offshore dump sites may also have been locations where waste material from metals processing or pharmaceutical production was disposed, although such activities no longer take place (EPA, 2023).

Several such dump sites are located around the South and West coast, and the material on the seabed here should be considered to be contaminated. Avoidance of these areas is highly recommended as disturbance of such sediments during cabling activities may lead to remobilisation of contaminants into the marine environment (BERR, 2008).

3.4.6.5 Shipwrecks

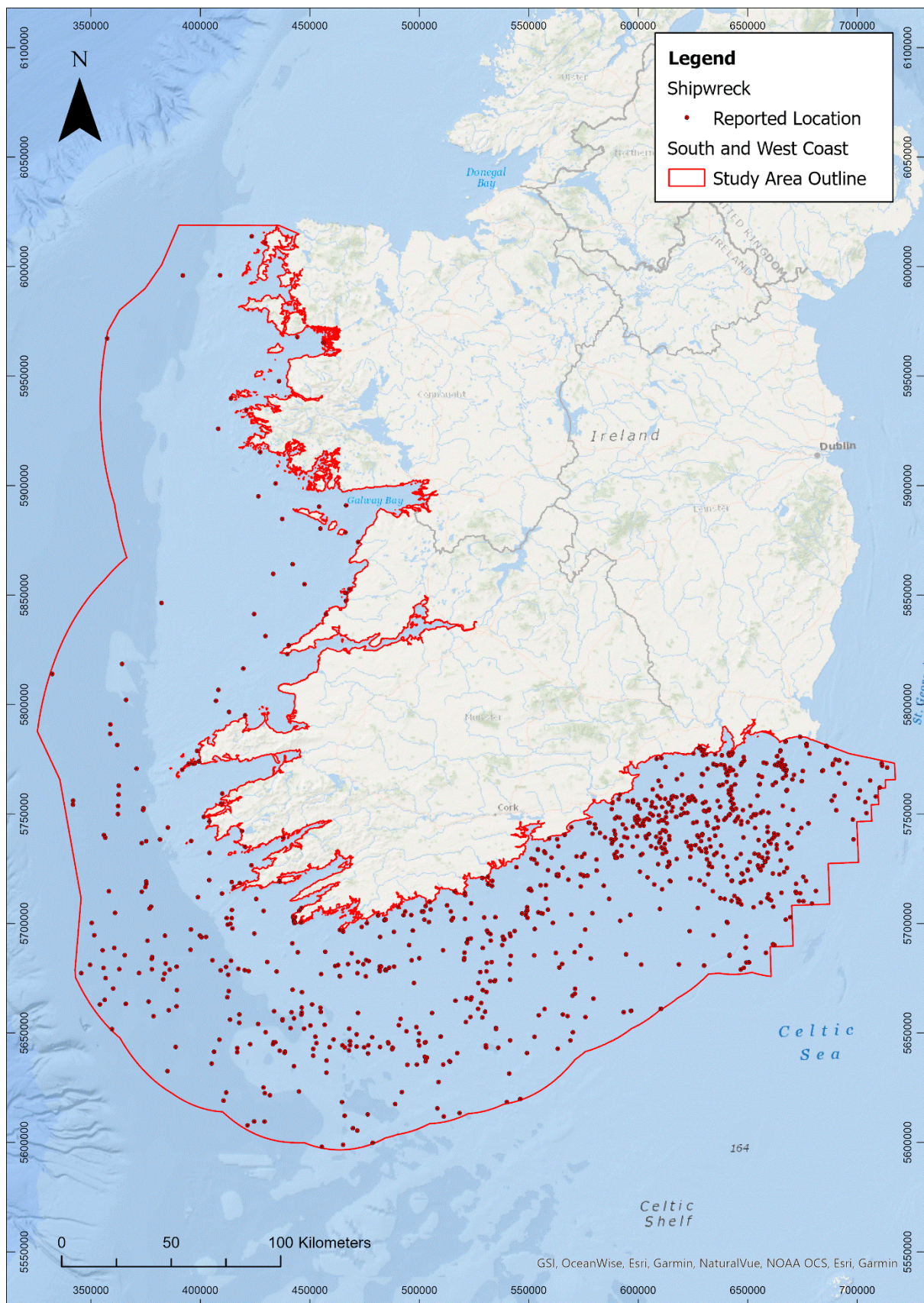


Figure 3.14: South and West Coast Shipwrecks (DHLGH, 2023a; INFOMAR, 2023b)

The National Monuments Service (NMS) contains an archive of over 18,000 shipwrecks in Ireland, located within Irelands maritime territory, as well its rivers, lakes and canals (DHLGH, 2022a). The sources of these records are numerous, such as from survey and navigational charts, historic newspapers and first-hand accounts from divers or fishermen (DHLGH, 2023). During its extensive mapping activities, INFOMAR has recorded over 540 shipwrecks, confirming the locations of many of reported shipwrecks, as well as identifying previously unknown wrecks (INFOMAR, 2024).

In Ireland, all newly discovered shipwrecks, and those over 100 years old, are protected archaeological sites (DHLGH, 2022a). For the purposes of this study, both the INFOMAR and NMS databases have been used and a 500 m buffer zone – based on the ICPC working zone (ICPC, 2013) – has been applied surrounding each of the 1,124 recorded wrecks in the study area.

3.4.6.6 Military Exclusion Zones

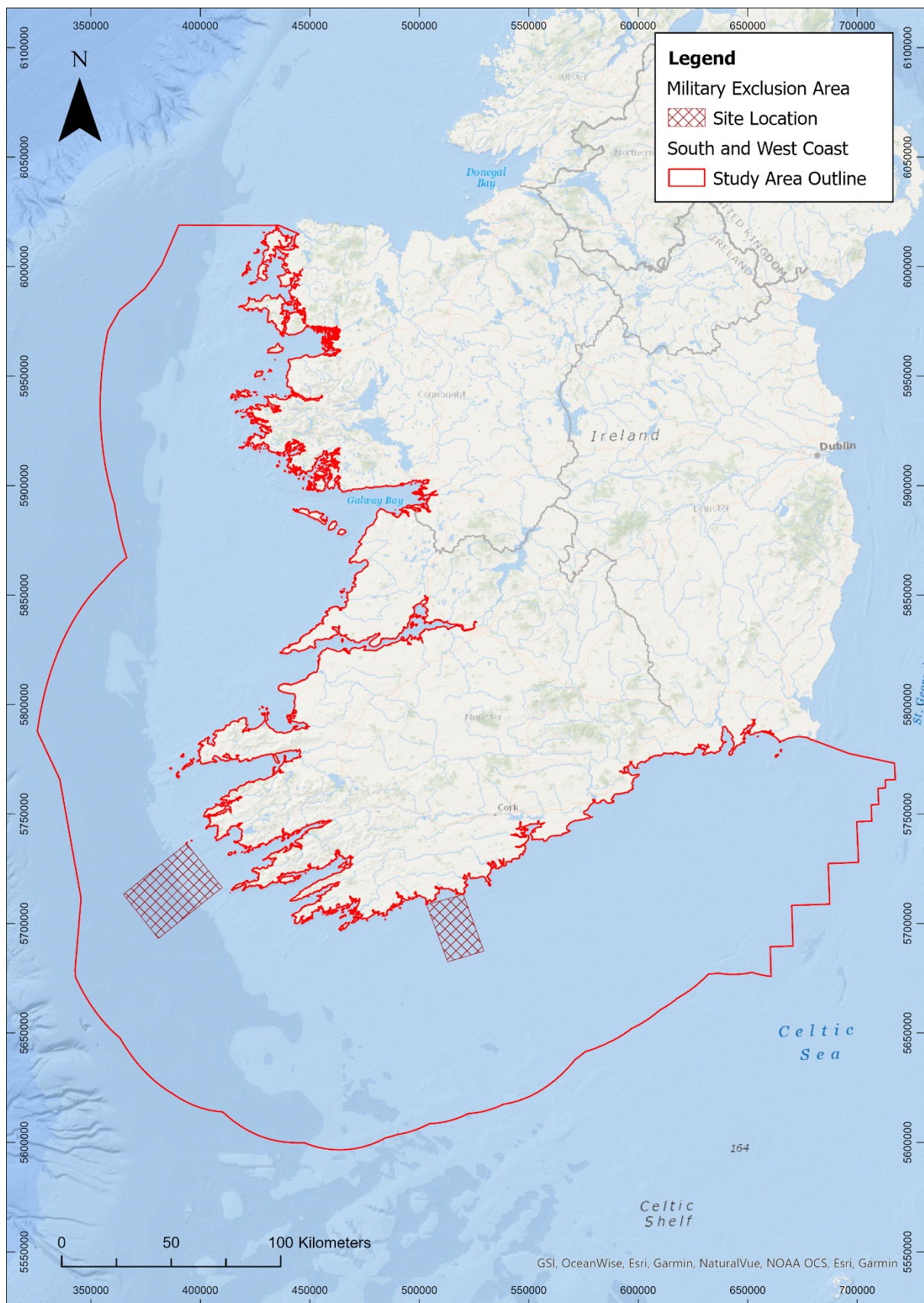


Figure 3.15: South and West Coast Military Exclusion Zones (EMODnet, 2022c)

Ireland has restricted areas for their military for the purposes of conducting training, testing, or firing exercises. These zones clearly pose a risk to ORE infrastructure. Two such areas are located within the South and West coast, with the boundaries defined by the Department of Defence (EMODnet, 2022c). Although installation of SECs may be possible within these zones, for the purposes of this study, these areas have been removed from the study area entirely.

3.4. Software

The spatial data used within the project was processed and analysed primarily through ArcGIS Pro software. ArcGIS Pro is a GIS software developed by Esri. This was selected due to its powerful spatial analysis and geoprocessing tools, such as the Weighted Overlay and Least Cost Path tools.

Additional processing and interpretation of sub-bottom profile data completed in SonarWiz 7. SonarWiz is a software produced by Chesapeake Technology and is tailored towards the processing and analysis of hydrographic and geophysical survey data.

3.5. Data Sources

Table 3.2: Criteria Layer Data Type and Sources

Criteria	Sub-Criteria	Name	Type	Source
Bathymetry		DTM Tiles: D3_2022_mean, E3_2022_mean & E4_2022_mean	Geotiff - Float 32bit	EMODnet, 2022b
Slope		IE_GSI_MI_Bathymetry_10m_Inshore_IE_WGS84_LAT_TIFF	Geotiff - Float 32bit	INFOMAR, 2023a
Substrate		IE_GSI_MI_Seabed_Classification_Folk_EUNIS_MSFD_WGS84_LAT_IE_Waters	Shapefile - Polygon	INFOMAR, 2023c
Substrate		ISSGM23_Solid_Earth	Shapefile - Polygon	Arosio <i>et al.</i> , 2023
Substations		Coastal_Substations	Registered Map	EirGrid, 2023c
Route Density		wid1000006-all_traffic-all_europe-yearly-20220101000000_20221231235959-tdm-grid.tif	Geotiff	EMODnet, 2022d
Protected Sites and Exclusion Zones	Cables	Celtic Interconnector	Registered Map	EirGrid, 2020
Protected Sites and Exclusion Zones	Cables	FR_SHOM_Câbles_télécommunication & NL_Rijkswaterstaat_Telecom_kabels_noordzee	Shapefile - Polyline	EMODnet, 2023
Protected Sites and Exclusion Zones	Cables	AEC2 subsea fibre optic cable	Registered Map	DECC, 2020
Protected Sites and Exclusion Zones	Cables	Iris Fibre optic cable	Registered Map	Orrason, 2022
Protected Sites and Exclusion Zones	Cables	Subsea Cables and Pipelines	Feature Service Feature Class	KIS-ORCA, 2023
Protected Sites and Exclusion Zones	Natura 2000 Sites	NHA_ITM_2019_06.shp, SAC_ITM_2023_10.shp, SPA_ITM_2023_05.shp	Shapefile - Polygon	NPWS, 2019; 2023a; 2023b
Protected Sites and Exclusion Zones	Aquaculture Sites	Aquaculture_Sites	Web Map Service	Department of Agriculture, Food and the Marine, 2018
Protected Sites and Exclusion Zones	Dumping Sites	DAS_DumpBoundaries	Shapefile - Polygon	EPA, 2023
Protected Sites and Exclusion Zones	Shipwrecks	IE_GSI_MI_Shipwrecks_IE_Waters_WGS84_LAT	Shapefile - Point	INFOMAR, 2023b
Protected Sites and Exclusion Zones	Shipwrecks	Wrecks20230728_table	csv - Point	DGLGH, 2023a
Protected Sites and Exclusion Zones	Military Exclusion Zone	EMODnet_HA_MilitaryAreas_pg_20221216	Shapefile - Polygon	EMODnet, 2022c

3.6. Data Processing

Once all the data was collected and imported into ArcGIS Pro, each of the six criteria layers was rasterised, re-classified and clipped to the extent of the study area. Each layer was resampled to a 100 m spatial resolution and re-projected to Coordinate Reference System UTM 29N. A ranking scale of 1 - 5 was adopted based on previous studies (see Makrakis *et al.* 2023; Taoufik and Fekri, 2023). The qualitative statement for each number was modified from Hassan *et al.* (2020), namely 1 – ‘Highly Suitable/Preferable’ 2 – ‘Suitable/Preferable’, 3 – ‘Marginally Suitable/Preferable’, 4 – ‘Unsuitable/Unpreferable’ and 5 – ‘Highly Unsuitable/Unpreferable’. The term ‘preferable’, rather than ‘suitable’, applies to layers where cable deployment is feasible throughout. For example, while SECs can technically be deployed in all water depths within the study area, shallower waters are considered preferable due to reduced installation and maintenance costs. The classification values for each criteria layer are listed in Table 3.3 below.

Table 3.3: Criteria Layer Classification Values

Bathymetry		Slope	
Depth (m)	Value	Slope (°)	Value
0 - 20	1	0 - 1	1
20 - 40	2	1 - 5	2
40 - 60	3	5 - 10	3
60 - 80	4	10 - 20	4
80 - 215.4	5	≥20	5
Distance to Grid		Vessel Density	
Distance (km)	Value	hr/km ² /year	Value
0 - 10	1	0 - 50	1
10 - 25	2	50 - 100	2
25 - 50	3	100 - 200	3
50 - 100	4	200 - 400	4
≥100	5	≥400	5
Substrate		Protected Sites and Exclusion Zones	
Folk Classification	Value	Description	Value
Sand	1	Outside Protected Sites and Exclusion Zones	1
Coarse Sediments	2	Existing Cable or Pipeline	3
Muddy Sediments/ Unclassified	3	Natura 2000 and Aquaculture Sites	4
Mud	4	Shipwreck	5
Bedrock	5	Offshore Dump Site	5

For the criteria which contain a range of values, namely Water Depth, Slope, Route Density and Distance to the Grid, each layer was classified based on logical breaks in the data, or through industry recommendations.

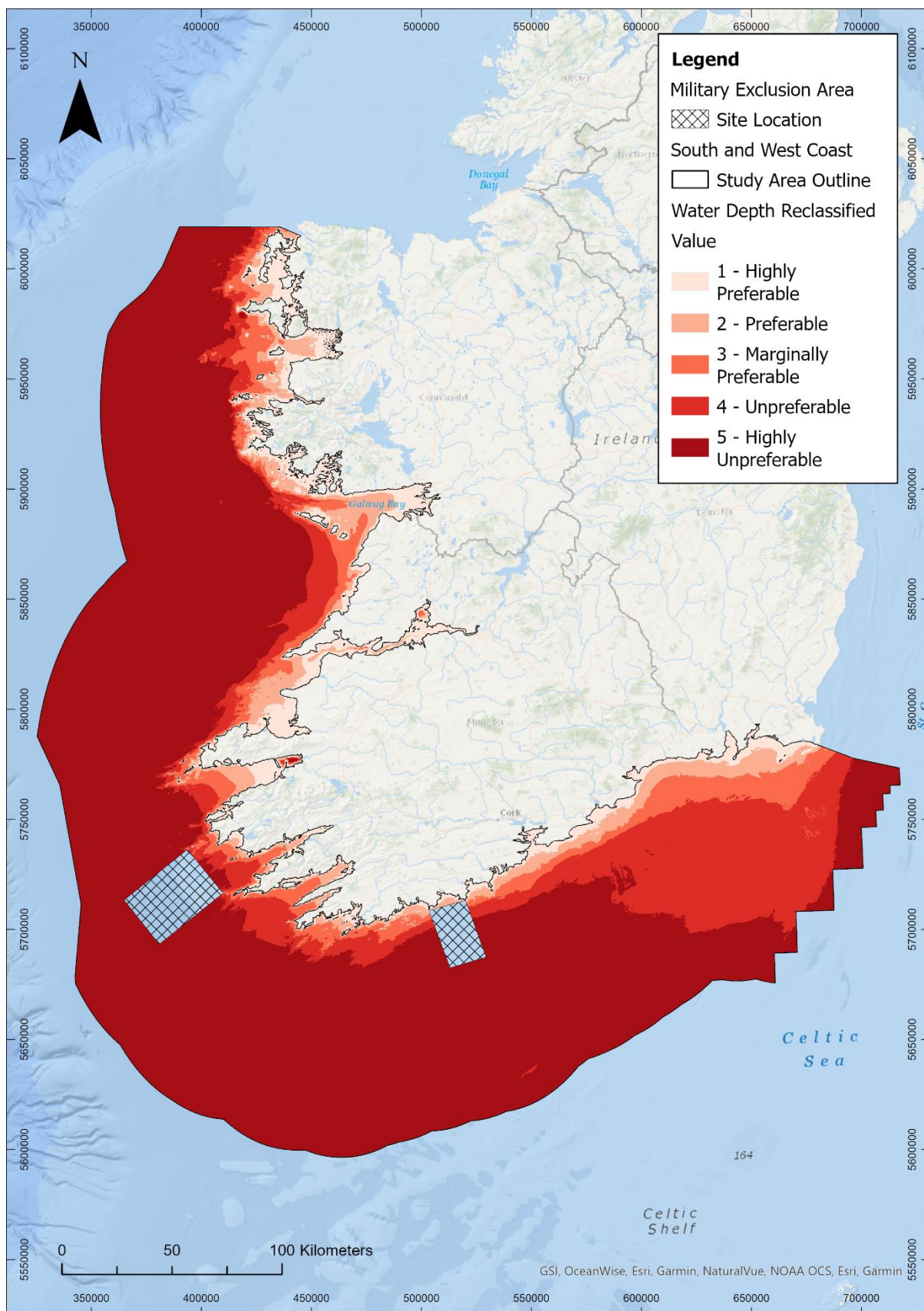


Figure 3.16: Reclassified Bathymetry Layer

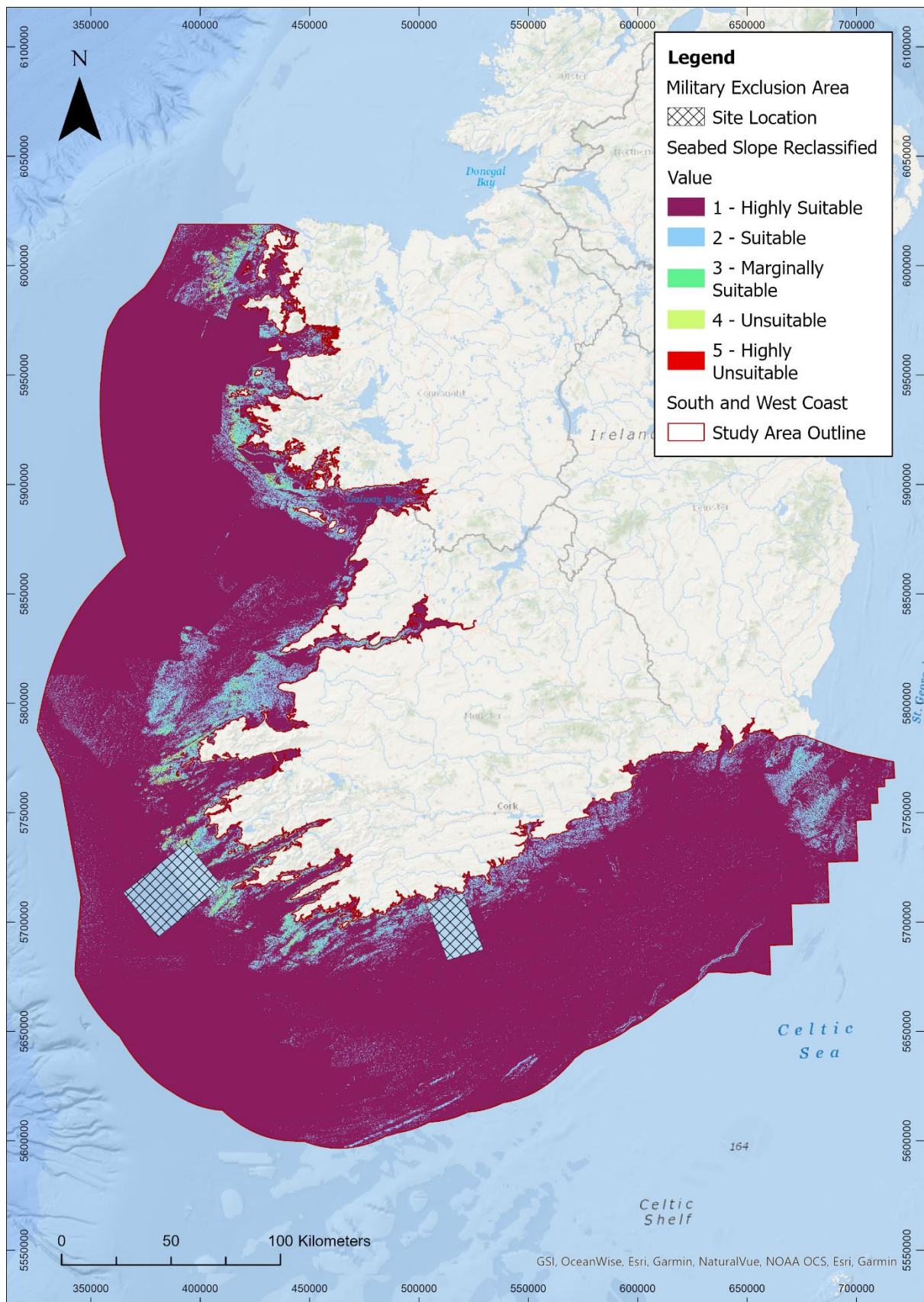


Figure 3.17: Reclassified Slope Layer

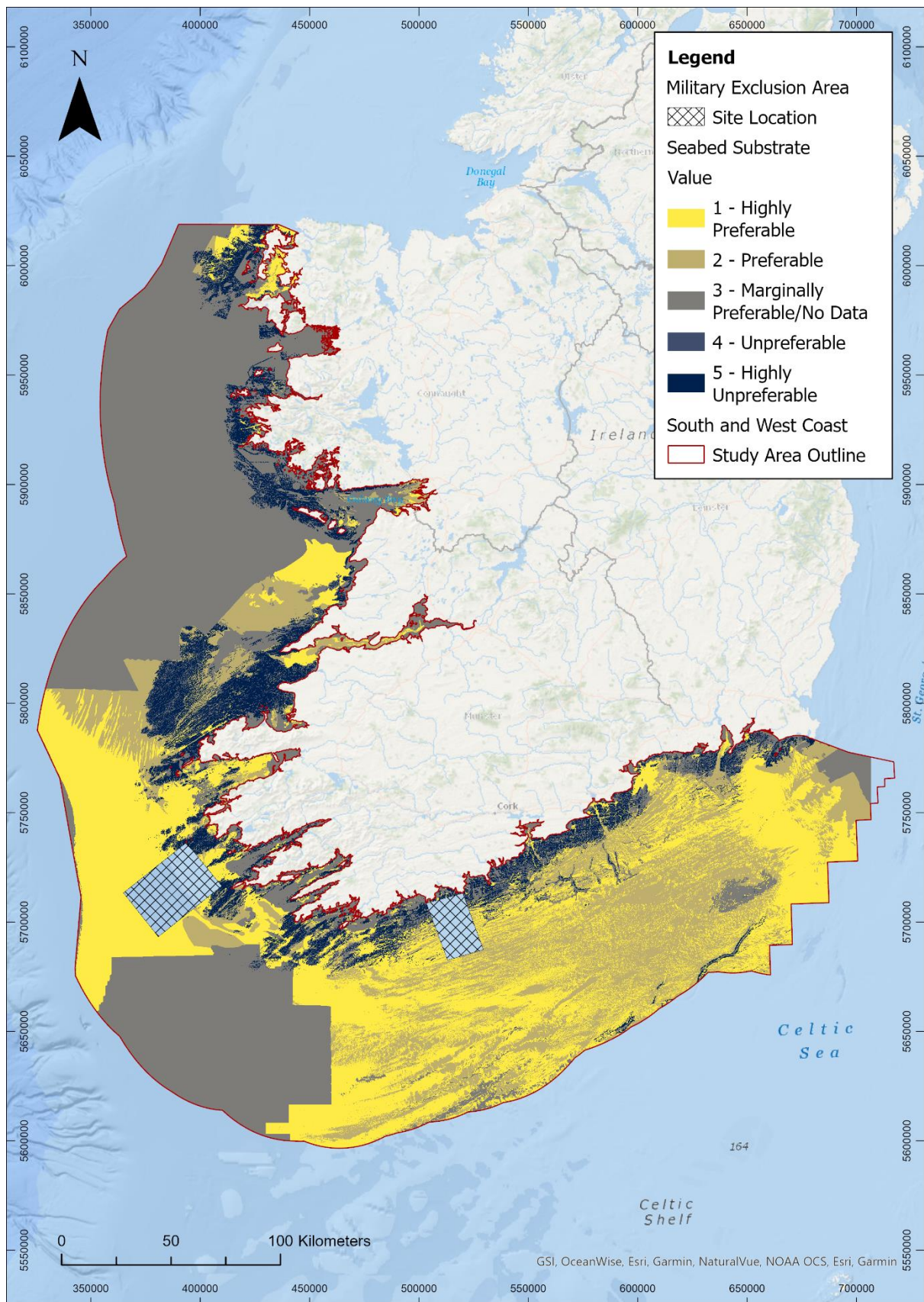


Figure 3.18: Reclassified Substrate Layer

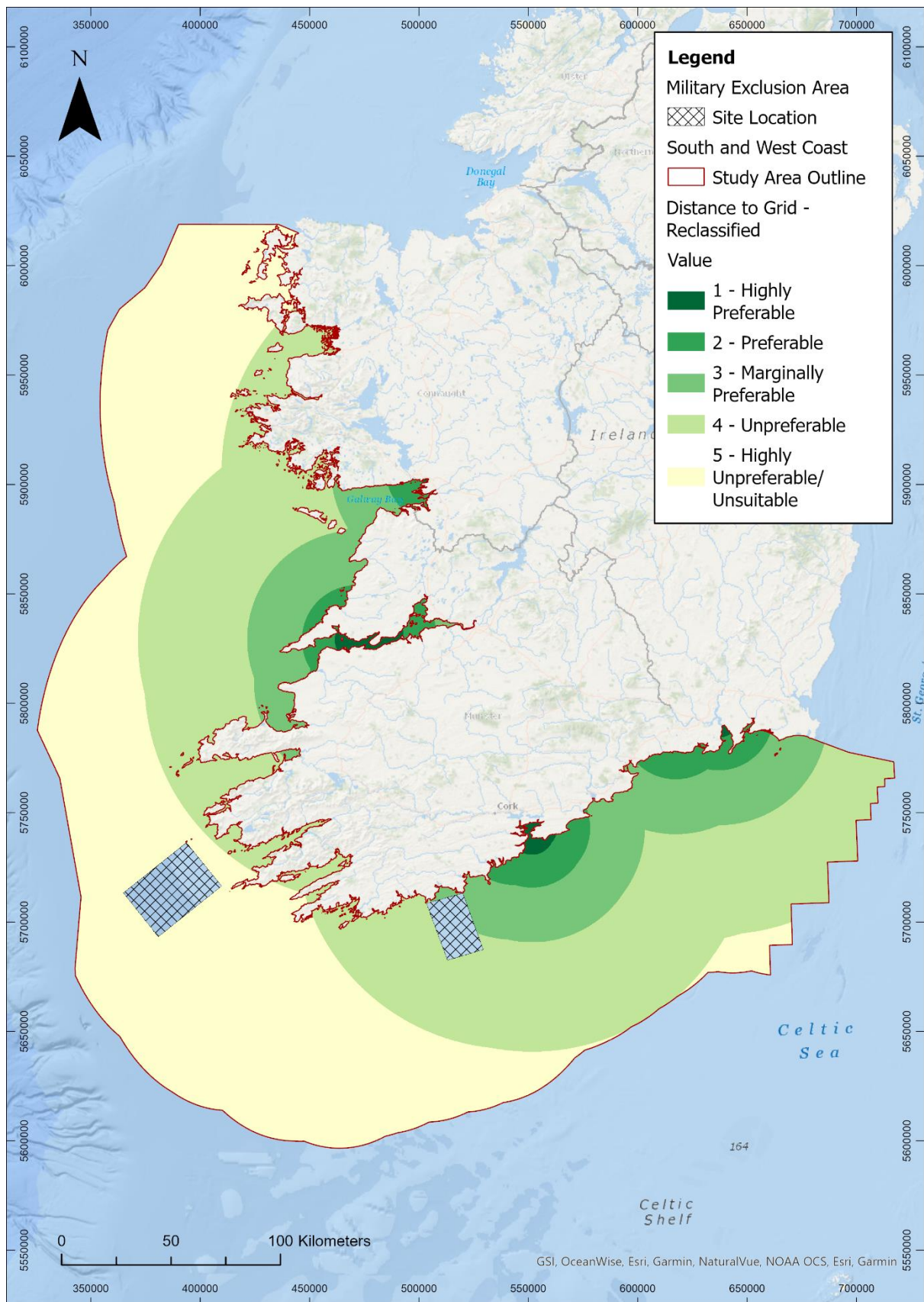


Figure 3.19: Reclassified Distance to Grid Layer

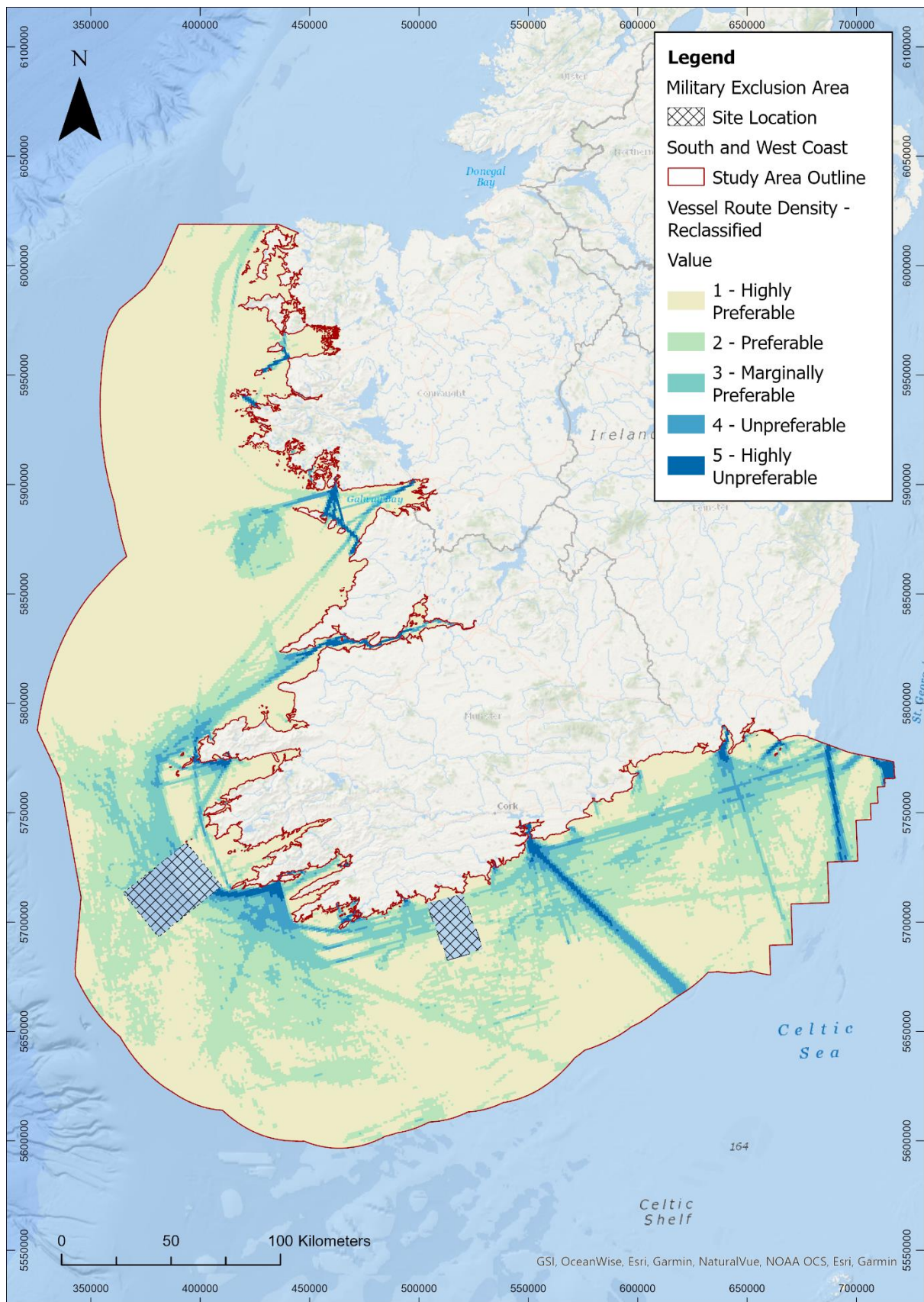


Figure 3.20: Reclassified Vessel Density Layer

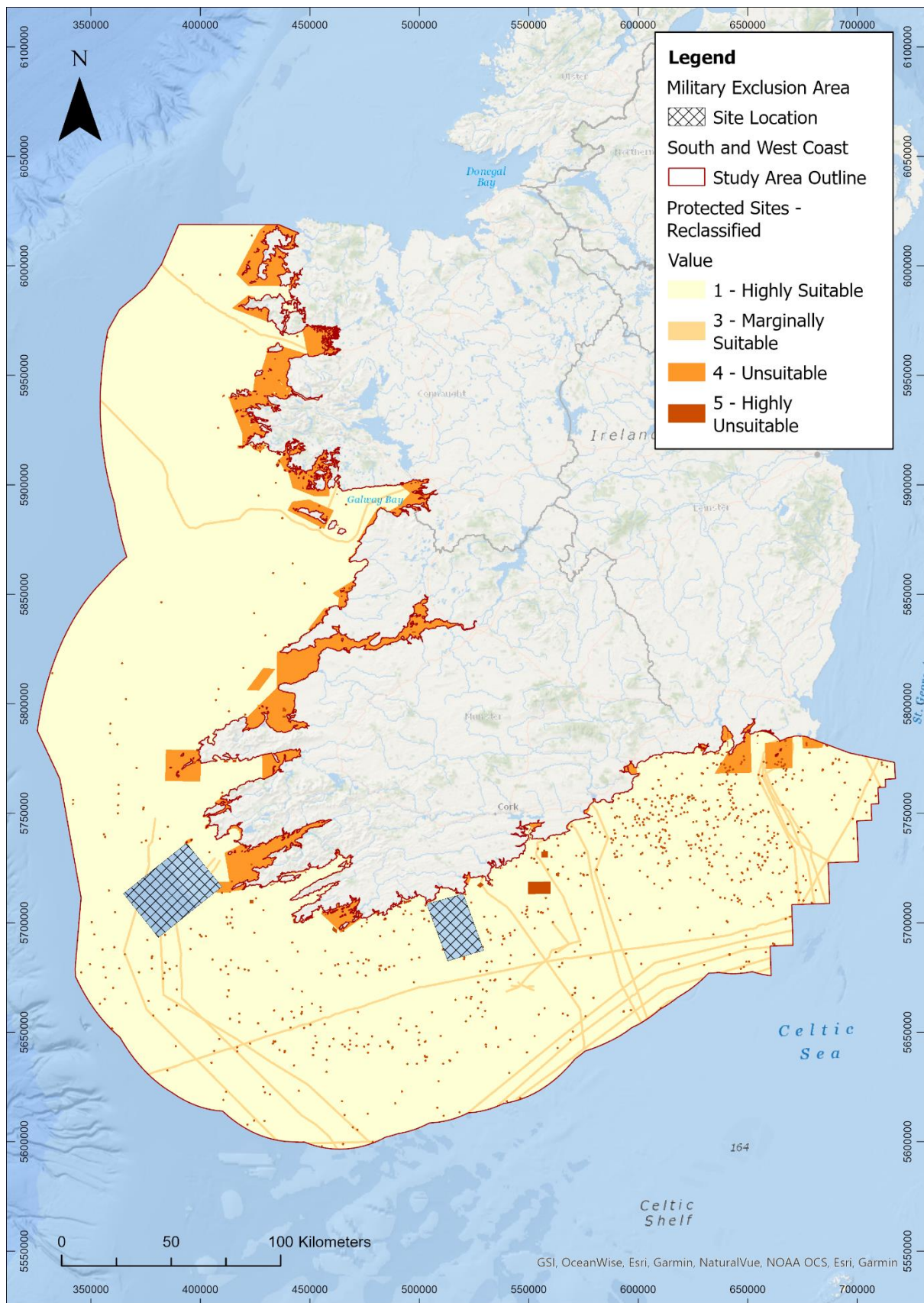


Figure 3.21: Reclassified Protected Sites and Exclusion Zones Layer

3.7. Multi-Criteria Decision-Making Analysis

The criteria discussed above are all influencing factors when assessing the suitability of an SEC route. However, the influence of each individual factor is not uniform, and some factors may conflict with each other. For instance, many coastal substations are situated near busy shipping lanes or environmentally sensitive areas. This necessitates a trade-off between the desire to locate a SEC as close to the existing grid as possible, whilst also avoiding hazardous or protected areas.

A Multi-Criteria Decision-Making Analysis (MCDA) is employed to evaluate the suitability of each layer. Combined with a GIS, an MCDA integrates value judgments into geographical data, thereby identifying the priority areas for any given outcome (Malczewski, 2006). See Sections 2.4 – 2.6 in the previous chapter for further details and examples from the literature.

The MCDA method chosen for this project is the Analytical Hierarchical Process (AHP), a widely used method in GIS-based site suitability analysis (e.g. Basharat *et al.*, 2016; Vasileiou *et al.*, 2017; Hassan *et al.*, 2020; Butschek *et al.* 2023; Topuz and Deniz, 2023; Makrakis *et al.*, 2023). AHP uses pair-wise comparisons to derive the relative importance or ‘weighting’ of one criterion over another (Saaty, 1987). Alternative MCDA methods were considered; however, AHP was chosen due to its transparency in reflecting the subjective judgments of the decision maker and its capability to assess the overall consistency of those judgments (Saaty, 1987).

AHP involves the use of a $n \times n$ comparison matrix, where a set of n elements, i.e. criteria, are compared against every other element, and the matrix is filled with the results of these comparisons. The comparison matrix A for three criteria (C1, C2, C3) has the following properties:

$$\mathbf{A} = \begin{pmatrix} 1 & a_{12} & a_{13} \\ \frac{1}{a_{12}} & 1 & a_{23} \\ \frac{1}{a_{13}} & \frac{1}{a_{23}} & 1 \end{pmatrix}$$

Where:

- a_{12} is the comparison value of C1 with C2,
- a_{13} is the comparison value of C1 with C3,
- a_{23} is the comparison value of C2 with C3,
- and $\frac{1}{a_{12}}$, $\frac{1}{a_{13}}$ and $\frac{1}{a_{23}}$ are the reciprocal values.

AHP uses the Fundamental Scale for determining these comparison values, see Table 3.4 below.

Table 3.4: The Fundamental Scale, adapted from Saaty (1987)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed between two adjacent judgments

In the case of the current project, the six criteria layers discussed previously were added to the comparison matrix. The value judgements for each comparison were based on the opinion of the author, informed by the literature and informal discussions with experts in the field. Upon completion of the pairwise comparison matrix, the sum of the values for each criterion is calculated. Each element in the comparison matrix is then divided by its column sum, and the average of these normalised values in each row is calculated. This average is the priority vector, or the criteria weight, and the sum of all weights will equal 1 (Saaty, 1987).

For these weighted values to have a reliable meaning, a consistency value must be calculated. This is achieved by first determining the principal eigenvalue (λ_{max}). This is calculated by multiplying each value of the comparison matrix by the priority vector for that criterion. The results for each criterion are summed and divided by the priority vector, and the average of all these provides the principal eigenvalue. A consistency index (CI) is then calculated using the formula:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

The next step is to determine the Random Index (RI), which is a predetermined value based on the number of criteria being analysed (Saaty, 1987). In this case, the RI value is 1.24 (Saaty, 1987). The consistency ratio (CR) is then calculated by:

$$CR = \frac{CI}{RI}$$

Some inconsistency is to be expected; however, for the results to be considered reliable, the CR value should not exceed 0.1 (Saaty, 1987).

In this study, a similar approach to that of Effat *et al.* (2022) was designed, involving the proposal of several scenarios, each with a different desired outcome. However, this approach differs in that all criteria are considered in each scenario. The weights for two scenarios were determined using AHP, while equal weighting was applied in the third scenario. In the first scenario, termed the Economic Scenario, the weighting is biased towards reducing the cost of the cable route, whilst also avoiding protected sites and exclusion zones, where possible. For the South and West Coasts, the two factors which will most influence this cost are the distance to the existing grid infrastructure, and the substrate type. This scenario is geared towards near-term projects, where the existing substations are the mostly likely grid connection points. Such projects could be those which have been authorised for development in Phases I and II of the ORESS, which is discussed in Section 3.8 (DECC, 2023c).

The second scenario, termed the Environmental Scenario, is aimed at addressing environmental concerns, with the avoidance of protected sites and exclusion zones considered most important. Substrate type is also considered highly influential in this scenario, since burial within optimal sediments will mitigate against potential negative impacts to the seabed, such as the introduction of foreign material or formation of suspended sediment plumes during cable burial (BERR, 2008). The existing grid infrastructure is considered least important in this scenario since the location of future coastal substations is currently unknown. This scenario could be seen as geared towards projects in later ORESS phases.

Once the weighting values for the three scenarios were calculated, a Weighted Overlay Analysis was performed in ArcGIS Pro to integrate the various data layers. This resulted in three suitability surfaces for the South and West Coast, with the entire area ranked on the same 1–5 scale described in Section 3.6. These values reflect the overall suitability for an SEC route for any 100 m cell within the surface. These surfaces comprehensively represent all the criteria and highlight the varying regions of suitability according to the specific concerns of each scenario.

3.8. Site Selection

Following completion of the suitability surfaces, focus was directed towards areas with current plans for offshore wind development. These areas have been selected and approved for development during Phases I and II of the ORESS. This scheme is the procedure in which ORE projects in Ireland can achieve a route to market and involves submitting bids in an auction to EirGrid, the nations power transmission operator (DECC, 2023c). These bids represent the price per megawatt hour (€/MWh) the ORE developer seeks to provide electricity, the average of which was €86.05/MWh for the four successful projects that took part in ORESS I in 2023 (WEI, 2023). One of these four projects, the Sceirde Rocks OWF, is situated within the South and West Coast. The project area for Sceirde Rocks is defined by the Maritime Area Consent allocated to the development. A Marine Area Consent grants a developer rights to occupy a maritime area in Ireland, for an OWF these areas include the turbine array area and the infrastructure corridors (DECC, 2022).

Phase II differs from Phase I in that it is State planners, not developers, that will be identifying the areas offshore suitable for ORE development, prior to issuing a Marine Area Consent. These regions will be defined within a series of Designated Maritime Area Plans (DMAPs) (DECC, 2023b). The first proposed DMAP region is also located in the study area, situated off the southern coast, and the proposal currently allows for one, 900 MW capacity wind farm to be sited in this region (DECC, 2023b).

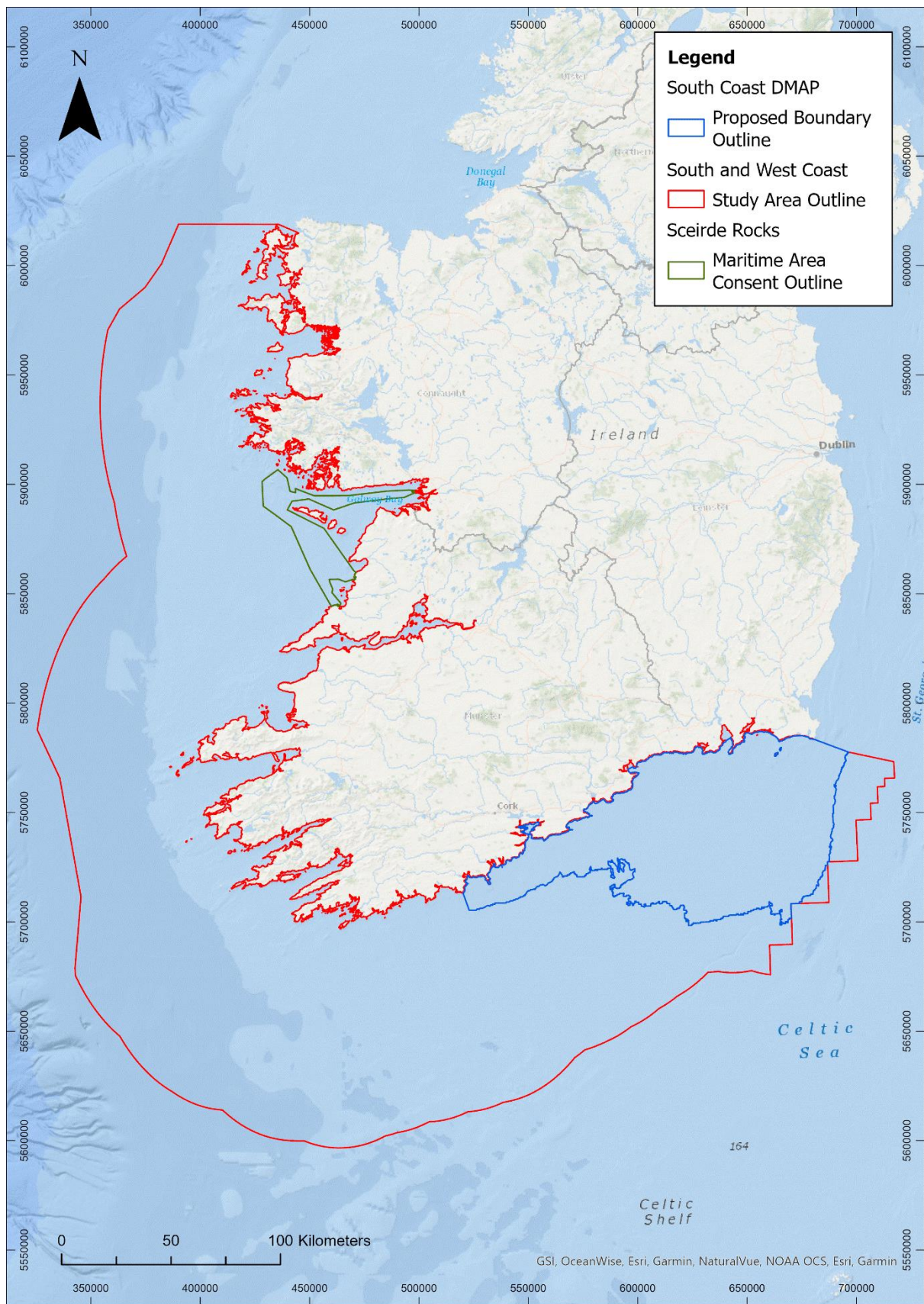


Figure 3.22: Location of Sceirde Rocks Offshore Wind Farm Project and South Coast DMAP

Further site selection within the Sceirde Rocks project outline area and South Coast DMAP boundary was required before SEC route selection methods could be implemented. As with any route, a SEC route must have a predetermined start and end point. In the case of an SEC from an OWF, the starting point is the offshore substation, and the end point is the onshore grid connection point, also known as the “landfall” site. For Sceirde Rocks, three corridors were already defined within the Marine Area Consent, and three corresponding landfall sites were selected for this study by the author at suitable locations at the coastline. The substation location was sourced from the preliminary windfarm layout, as per the project website (FST, 2023).

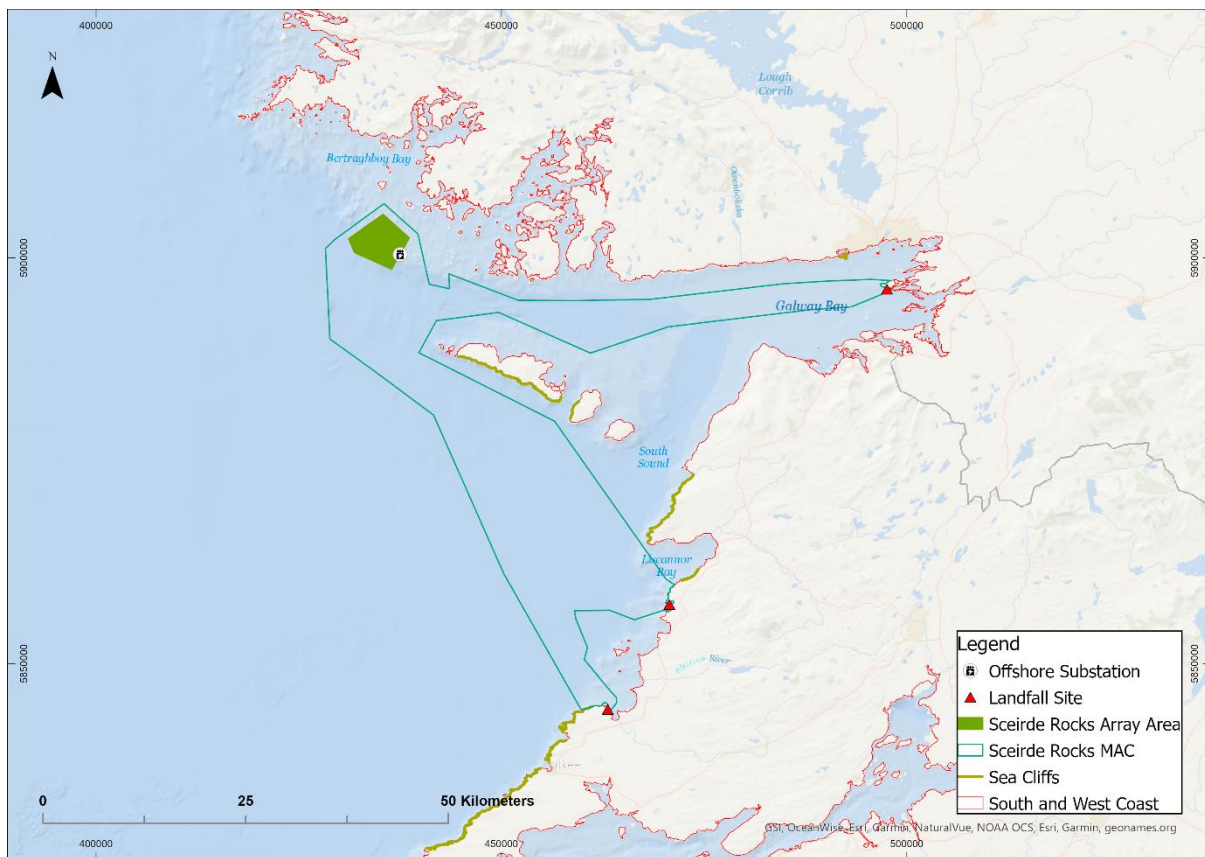


Figure 3.23: Sceirde Rocks Offshore Windfarm Project (Maritime Area Regulatory Authority, 2022)

The south coast DMAP has yet to be refined with exact OWF sites or cable route corridors. As such, the entire area was assessed for SEC route suitability. Potential substations were placed at the 12 nm (nautical mile) limit, which is over 22 km, at 1 km intervals. This distance marks the outer boundary of a coastal state’s territorial sea, as defined by the United Nations Convention on the Law of the Sea (UNCLOS, 1982). The limit is measured from a baseline which is typically the low-water line (UNCLOS, 1982). However, for frequently “indented” coastlines such as those surrounding the South and West Coast, the baseline may be simplified by connecting headlands with straight lines, maintaining a smooth baseline parallel to the coast

(UNCLOS, 1982). This limit was chosen as appropriate for this study due to the reduced visual impact of an offshore substation at such a distance from the coastline (Cronin *et al.*, 2021).

Numerous landfall sites were selected along the coastline of the DMAP area, which were selected in a more targeted fashion. The South and West coast is bounded by sea cliffs, many of which support diverse ecosystems and are classified as Annex I habitats under the EU Habitats Directive (Barron *et al.*, 2011). A polyline shapefile, produced by Barron *et al.* (2011), was used in the project to highlight these areas (see Figure 3.23 and Figure 3.24). There are also additional engineering requirements to bring an SEC onshore at a cliff site, such as directional drilling, which may add significant costs during installation (BERR, 2008). As such, avoidance of sea cliffs has been recommended and landfall sites have been selected along beaches, harbours and inlets along the southern coast.

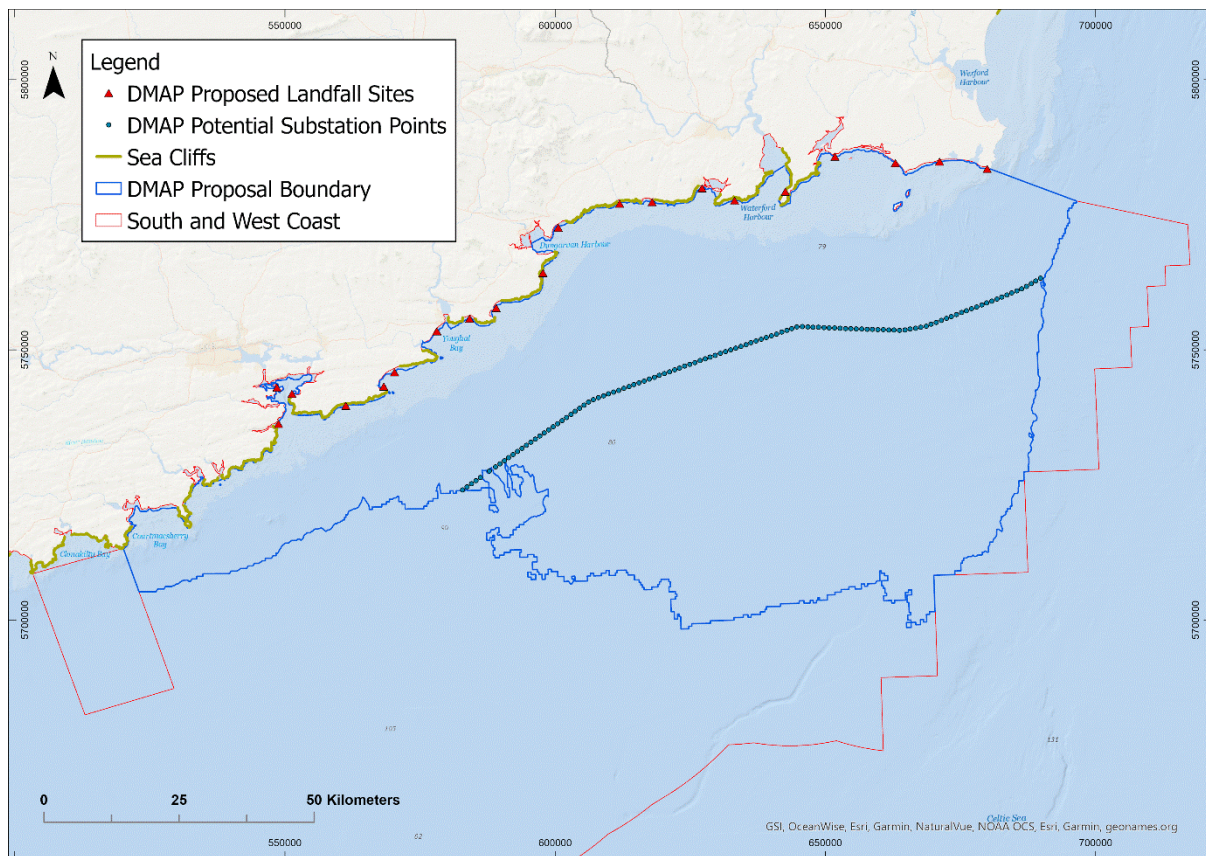


Figure 3.24: South Coast DMAP Site with Potential Offshore Substation and Landfall Locations (DHLGH, 2023b)

3.9. Route Selection

With the three essential elements for route selection finalised—the suitability surface, the start points, and the end points—GIS-based methods were reviewed and implemented to identify the optimal routes for SECs in the project areas. The method chosen was the Least Cost Path Analysis (LCPA), a frequently utilised tool in similar studies (e.g. Kang and Lee, 2017; Wang *et al.*, 2019; Makrakis *et al.*, 2023).

LCPA is a GIS technique used to find the most efficient route between two points, minimising the cost associated with traversing the landscape or surface. In this case, the “cost” refers to the suitability score, with lower scores referring to more suitable routes. LCPA is a variation of Dijkstra’s Algorithm, a method of determining the shortest, or least cost, path between a set of weighted nodes on a graph (Dijkstra, 1959). This process involves creating a path through a graph, starting at a source node, and assigning a distance value to every other surrounding node. The next step is to visit a neighbouring node and calculate the distances from the source node to that node. This process continues in an iterative fashion until the destination is reached. The path is then backtracked through the nodes to find the path with lowest total distance value.

ArcGIS Pro is equipped with the Least Cost Path tool, which automates this route selection process. It benefits from the ability to produce paths from multiple starting, and ending, points. The result is a series of routes along the seabed, strategically located in areas where adequate cable burial is possible while avoiding obstacles, hazards, and exclusion zones. The resulting paths were then refined using the “Smooth Line” tool in ArcGIS Pro, applying the Polynomial Approximation with Exponential Kernel smoothing algorithm, with a smoothing tolerance of 500 m. This was chosen to minimise the number of sharp course-alteration angles along the route while preserving the detailed information obtained from the suitability surfaces at a resolution that was not greatly coarser than the rasters the LCPA was built upon. The paths were then ranked based on overall length and suitability. For the DMAP region, additional processing of sub-bottom profile data was completed in the most suitable areas.

3.10. Sub-bottom Profile Data

The SEC routes identified during the LCPA highlighted two key areas within the DMAP region. Although these areas are highly suitable, significant exposures of bedrock on the seabed and the presence of sediment with insufficient thickness for burial present challenges. The Irish Government's DMAP proposal states that cable burial within the seabed sediment should be prioritised wherever possible (DECC, 2024). Therefore, by understanding the sediment thickness variations across the area, the most suitable routes for adequate cable burial can be selected accordingly.

Sub-bottom profile (SBP) data are acquired in much the same way as MBES data. Essentially, a low frequency acoustic signal is emitted from a source, or transducer, directed at the seabed (Plets *et al.*, 2013). Depending on the composition of the seabed and the type of profiler used, this acoustic signal may penetrate into the sediment, reflecting off individual layers or "horizons". The time it takes for these reflections to return to the transceiver is used to determine the depth, and the amount of energy returned offers insights into the composition of the reflecting layer (Jakobsson *et al.*, 2016). Depending on the sediment type and system of sub-bottom profiler used, a vertical profile of up to 50 m can be attained (INFOMAR, 2021).

INFOMAR provides SBP data over a large portion of the South and West Coast, collected as part of numerous seabed mapping surveys. These data were collected via a SES 5000 2x2 array, a "Pinger" system which emits a 4 kHz frequency in a single pulse (INFOMAR, 2021). For the purposes of this study, data from seven INFOMAR surveys were downloaded, and individual survey lines were processed. This was limited to the most suitable areas within the south Coast DMAP region, the results of which are detailed in Sections 4.2.2 and 4.3.2.

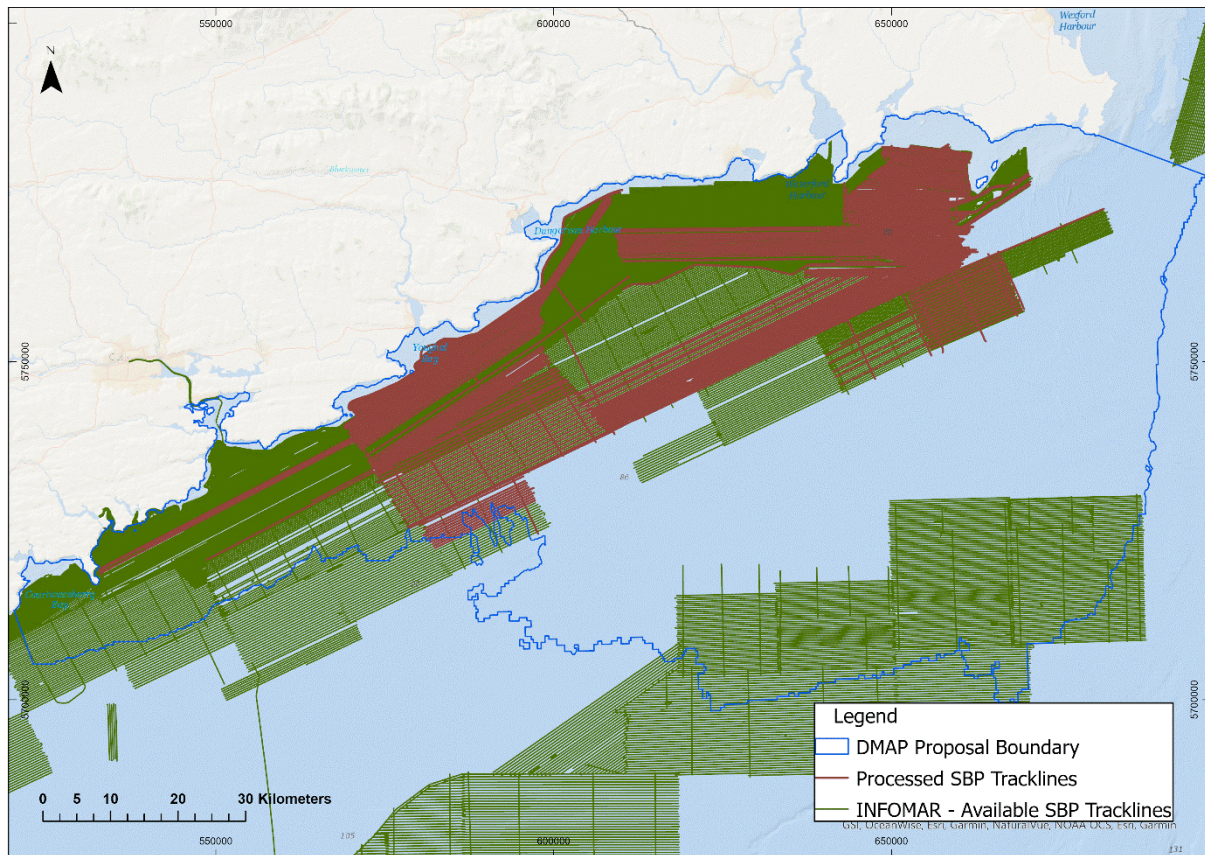


Figure 3.25: Available and Processed SBP Track lines – South Coast DMAP

The INFOMAR SBP dataset is saved in the SEG-Y format, which was developed specifically for geophysical data. This was imported into SonarWiz, where the files are converted to CSF format, and intermediate file format specific to SonarWiz. The locations and depths of the SBP data were then validated against the INFOMAR bathymetric grid, which was uploaded into SonarWiz as a Geotiff at a 10 m resolution. SonarWiz contains a “bottom-track” tool, which can automatically detect the first reflector, i.e. the seafloor, within the SBP data (see Figure 3.26 below).

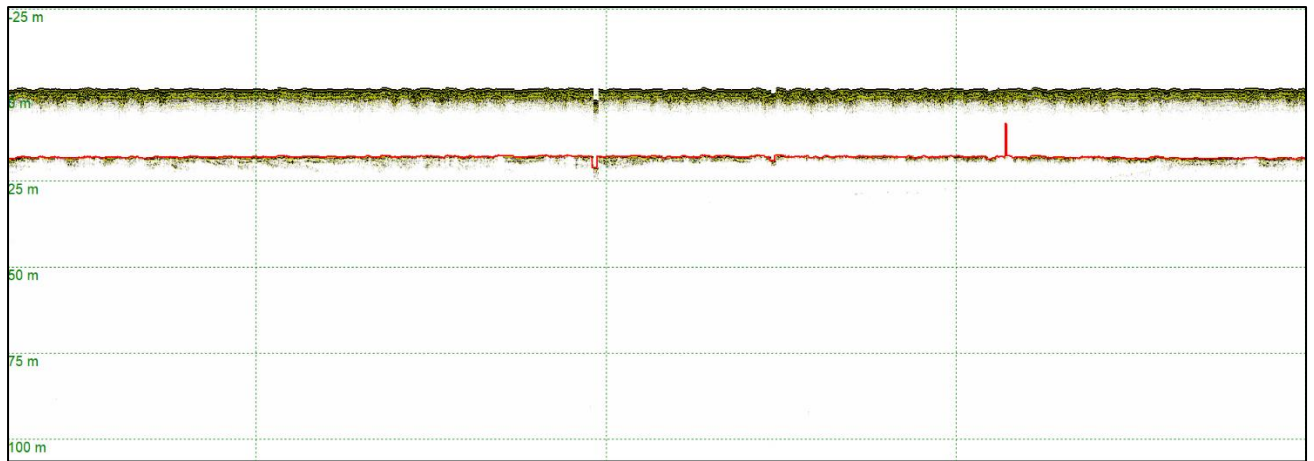


Figure 3.26: Line_19_230413.092017.sgy from survey CV13_01 – Pre-processing

Once the data were bottom-tracked, customised gain settings were applied to visually enhance the data and remove some of the noise within the water column. Any residual spikes in the data (e.g. Fig 3.27) were manually removed. Often, a vertical offset correction was applied to this surface, utilising the “Bathy Grid Separation” tool to match the seafloor in the CSF file to that of the INFOMAR bathymetry grid (see Figure 3.28 below). This was implemented to remove noise in the data – which may have been caused by the weather conditions at the time of surveying or equipment issues – and correct for offsets in the vertical offshore reference datum. This simultaneously reduced the SBP data to lowest astronomical tide (LAT).

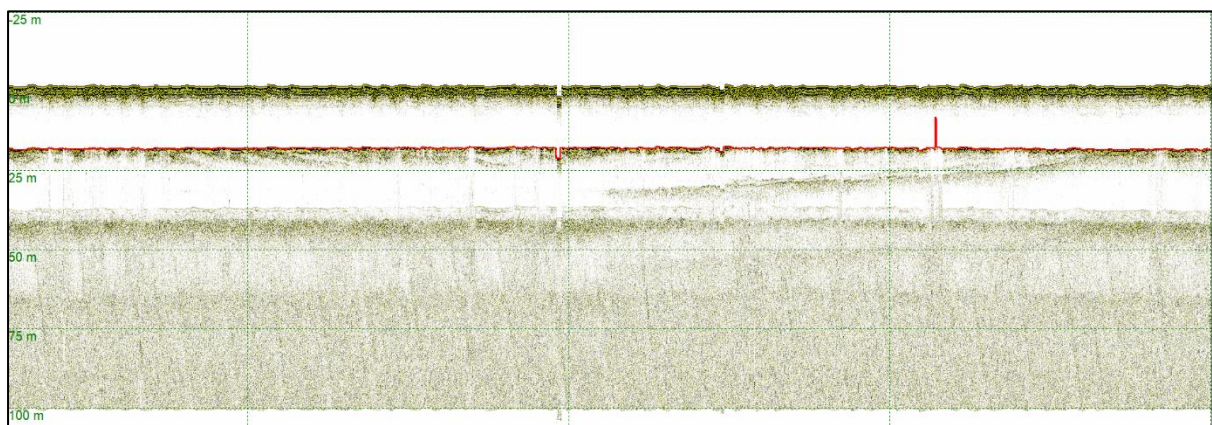


Figure 3.27: Line_19_230413.092017.sgy from survey CV13_01 - bottom tracked with gains applied

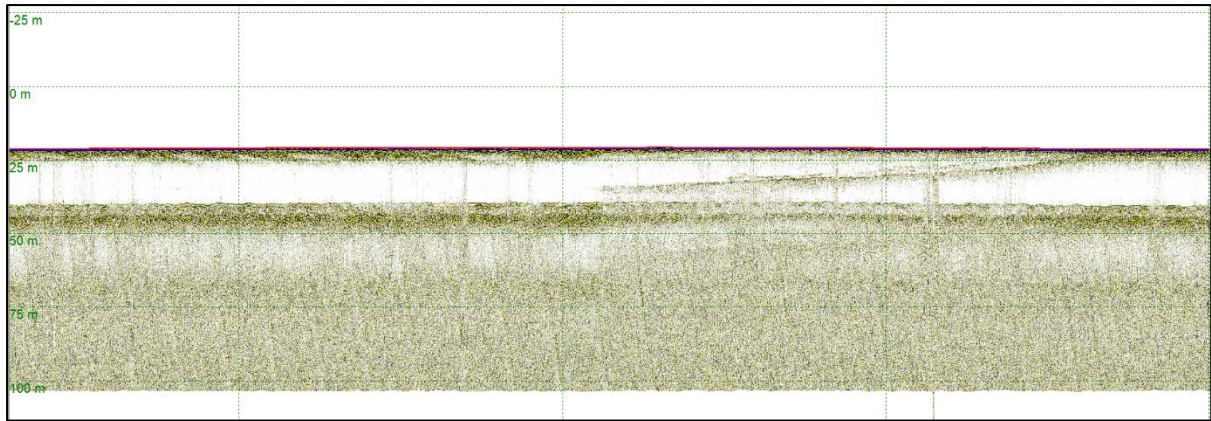


Figure 3.28: Line_19_230413.092017.sgy – Post Processing

At this point, individual reflectors could be interpreted. This involved analysing each SBP line and manually digitising reflectors, see Figure 3.29 below as an example. The unique style or morphology of reflectors identified during processing led to the classification of four seismic units (SUs), with the naming conventions adapted from similar work off the south coast of Cork by Toth *et al.*, (2020). Once the SUs for each line were digitised, the thickness of each was computed by the software package by subtracting the seafloor depth from the depth to the base of the unit. The calculation employed a default sediment sound velocity of 1,600 m/s, which is representative of the acoustic properties typically observed in sandy and mixed coarse sediments (Wang *et al.*, 2021a). This value was deemed appropriate for this study due to the widespread prevalence of such sediment types throughout the study area (Figure 3.5).

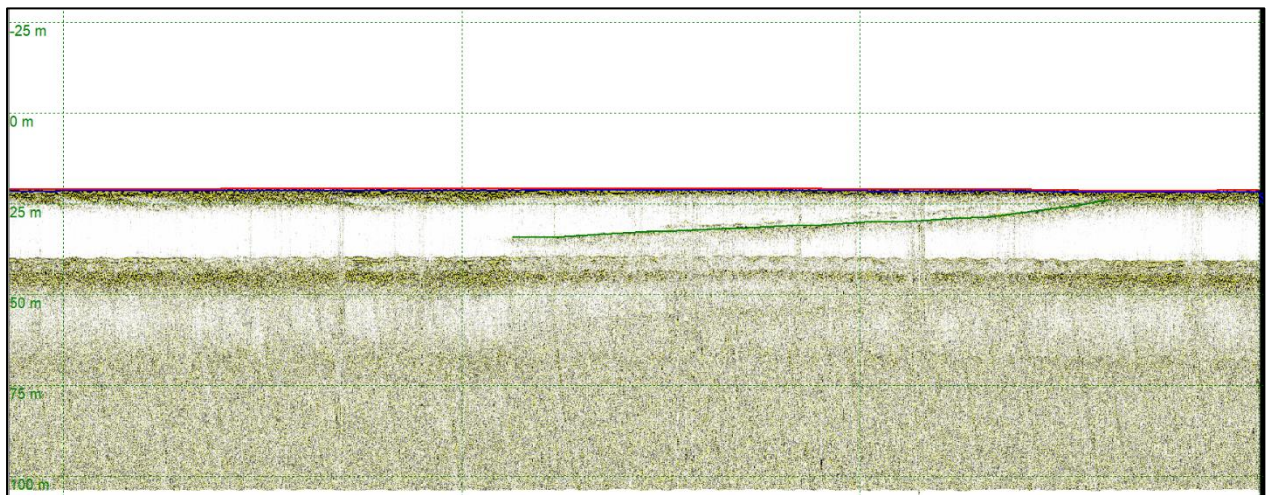


Figure 3.29: Example of a Digitised Seismic Reflector

This process was repeated in an iterative fashion until each of the chosen lines within the study area was analysed. The result was a series of points along each processed line indicating the thickness of the seismic unit at that location. Using these point data, a sediment thickness map

was created for two areas within the south coast DMAP. To generate two continuous surfaces, the maximum unit thickness readings were interpolated using Empirical Bayesian Kriging (EBK) interpolation in ArcGIS Pro. EBK is based on Kriging, a geostatistical interpolation procedure which predicts the value of a variable, in this case sediment thickness, at unsampled locations on a surface. The method utilizes the distance and direction between points to reflect spatial correlation, with weights defined by the distances between measured points and their overall spatial arrangement (Esri, n.d.).

The semivariogram, which quantifies how the spatial autocorrelation of a variable changes with distance, expresses the rate of variance between measured points (Diggle and Ribeiro, 2007). Unlike traditional kriging methods that require manual fitting of a theoretical semivariogram model, EBK automates this process through an iterative approach, with 100 simulations used for each modelled surface (Esri, n.d.). Bayesian inference incorporates the degree of uncertainty in semivariogram simulations based on the observed data, producing a posterior distribution of semivariograms that best represent the spatial correlation (Aelion *et al.* 2009). These posterior semivariograms are then used to make predictions at unsampled locations and the average of these values produces the result. This approach provides both the predicted value for sediment thickness at an unsampled location, and the degree of uncertainty for that prediction (Esri, n.d.).

Deterministic methods of interpolation were also tested, such as Inverse Distance Weighting and Radial Basis Functions. EBK was chosen due to its ability to identify and model trends in the data. Some of these trends correspond to known features in the seabed, such as the orientation of paleochannels.

Once the sediment thickness surfaces were completed, each area was clipped to the coastline and areas of mapped bedrock were removed from the grids. The LCPA was performed again for the routes identified in Section 3.9, producing routes which preferentially select areas with the thickest sediment.

4. Results

This chapter presents the findings from the geospatial analysis to identify the most suitable sites, and optimal routes, for submarine export cables (SECs) within the South and West Coast of Ireland. The first section focuses on the outcomes of the criteria weighting process using the Analytical Hierarchical Process (AHP), with three scenarios discussed. The second section examines the suitability surfaces generated from these weight values, using a weighted overlay analysis. These suitability surfaces form the foundation upon which a Least Cost Path Analysis (LCPA) was conducted to create optimised SEC routes. These routes are described in the third section of this chapter. The final section presents the results of the Sub-Bottom Profile (SBP) analysis and sediment thickness interpolation, where key routes are further optimised.

4.1. Multi-Criteria Decision-Making Analysis

The six key influencing criteria identified for this study (detailed in Section 3.3) were assessed through AHP to derive weighted values for each layer. Given the number of variables and to mitigate against introducing bias towards any one consideration, three scenarios were envisaged:

- **Economic Scenario:** This scenario assesses the economic suitability of the South and West Coast for an SEC route, with a moderate level of risk considered tolerable. It is aimed at near-term offshore windfarm projects. Existing coastal substations are considered the main controlling factor on overall cable length. Burial in a suitable substrate and avoidance of bedrock is determined to be the next highest priority. Avoidance of protected sites and exclusion zones is also considered important. Water depth is considered but not deemed highly influential, given the depth ranges in the study area. Vessel route density is not considered impactful, since burial in suitable sediments should provide adequate protection against the hazards associated with dense vessel routes. Slope is regarded as the least important, since the highest slope areas most frequently coincide with exposed bedrock, the avoidance of which has already been accounted for in the substrate layer.
- **Environmental Scenario:** This scenario is aimed at determining the most environmentally appropriate regions of the study area for SEC routes and is also a more risk-adverse model. Avoidance of protected sites and exclusion zones is considered the main influencing criteria, given these are often associated with environmentally, or culturally, sensitive areas. The substrate is considered to be of next highest importance, since burial will reduce the need to introduce foreign material into the environment, from protection measures such as rock dumping or concrete mattresses (BERR, 2008). Burial in coarse sediments will also mitigate against the formation of sediment plumes during cable installation, which tend to be associated with soft, muddy sediments and may be harmful to marine life in the vicinity (BERR, 2008). Avoidance of routes with dense marine vessel activity and high slope areas is assigned moderate importance. Water depth is deemed somewhat influential, since monitoring of installation activities is likely to be more feasible at shallower depths. Since new substations are planned for construction, and their locations are currently unknown, the distance from the onshore grid is considered the least important factor. This scenario is aimed at future projects, assuming that near-term projects will utilise the existing coastal substations.

- **Equal Weighting Scenario:** Equal weighting was applied to the six criteria layers.

Table 4.1: Economic Scenario - Pairwise Comparison Matrix

Criteria	Distance to Grid	Substrate	Protected Sites & Exclusion Zones	Water Depth	Vessel Density	Slope	Criteria Weights
Distance to Grid	1	3	3	5	7	9	42.4%
Substrate	1/3	1	3	3	5	7	24.7%
Protected Sites & Exclusion Zones	1/3	1/3	1	1	3	5	12.6%
Water Depth	1/5	1/3	1	1	3	5	11.6%
Vessel Density	1/7	1/3	1/3	1/3	1	3	5.9%
Slope	1/9	1/7	1/5	1/5	1/3	1	2.9%

Table 4.2: Environmental Scenario - Pairwise Comparison Matrix

Criteria	Protected Sites & Exclusion Zones	Substrate	Vessel Density	Slope	Water Depth	Distance to Grid	Criteria Weights
Protected Sites & Exclusion Zones	1	3	3	5	7	9	42.4%
Substrate	1/3	1	3	3	5	7	24.7%
Vessel Density	1/3	1/3	1	1	3	5	12.6%
Slope	1/5	1/3	1	1	3	5	11.6%
Water Depth	1/7	1/3	1/3	1/3	1	3	5.9%
Distance to Grid	1/9	1/7	1/5	1/5	1/3	1	2.9%

Table 4.3: Equal Weighting Scenario

Criteria	Criteria Weights
Substrate	17%
Protected Sites & Exclusion Zones	17%
Water Depth	17%
Distance to Grid	17%
Slope	16%
Vessel Density	16%

The consistency ratio calculated for the pairwise comparison matrix shown above in

Table 4.1 and Table 4.2 is 0.04, with values below 0.1 considered reliable (Saaty, 1987).

4.1.1 Weighted Overlay Analysis

The resulting weights derived through AHP, shown in Table 4.1 and Table 4.2, and the equal weights shown in Table 4.3, were combined using the ‘Weighted Overlay’ tool in ArcGIS Pro. This resulted in three suitability surfaces, shown below in Figure 4.1, Figure 4.2 and Figure 4.3 respectively.

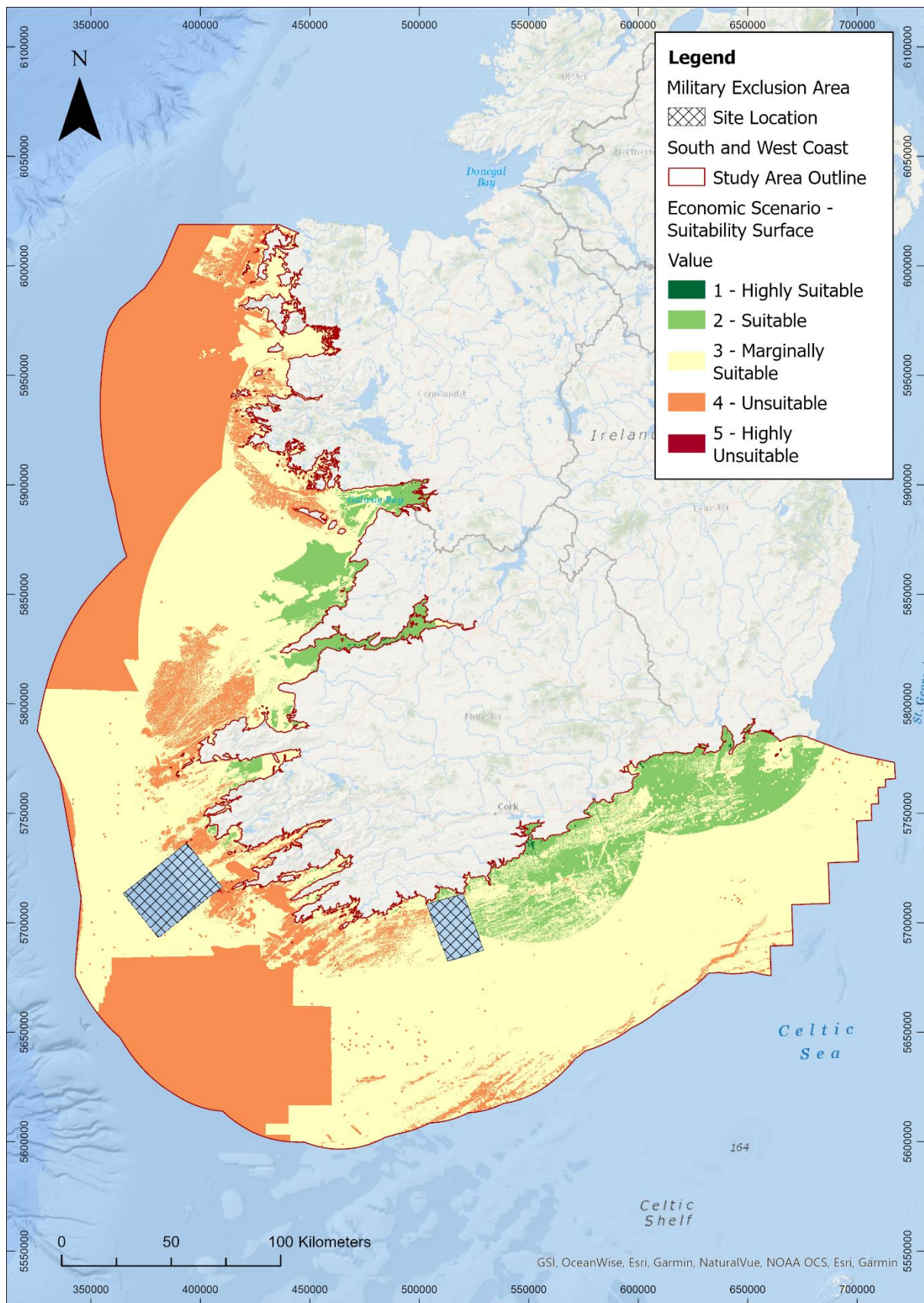


Figure 4.1: Economic Scenario - Suitability Surface

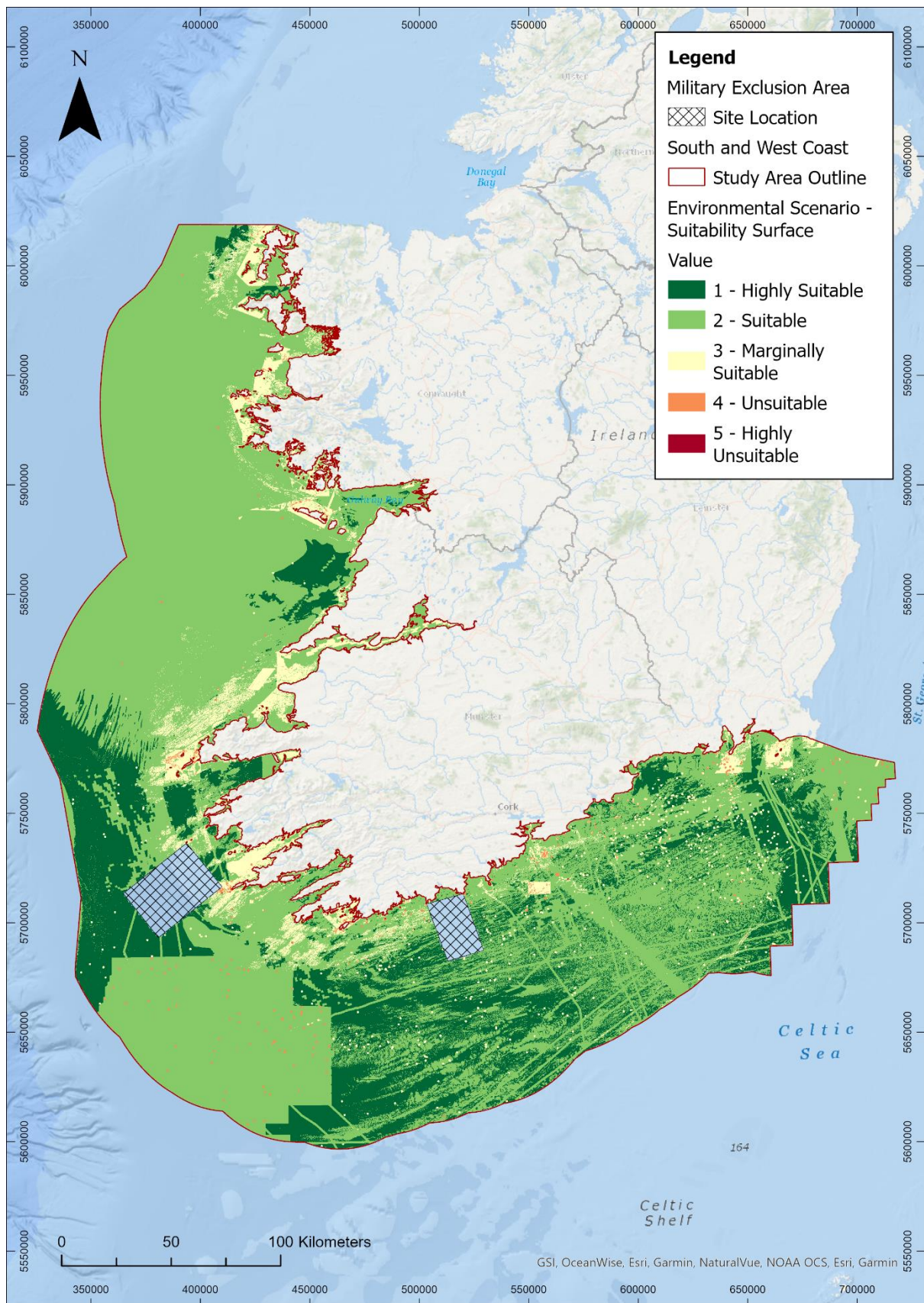


Figure 4.2: Environmental Scenario - Suitability Surface

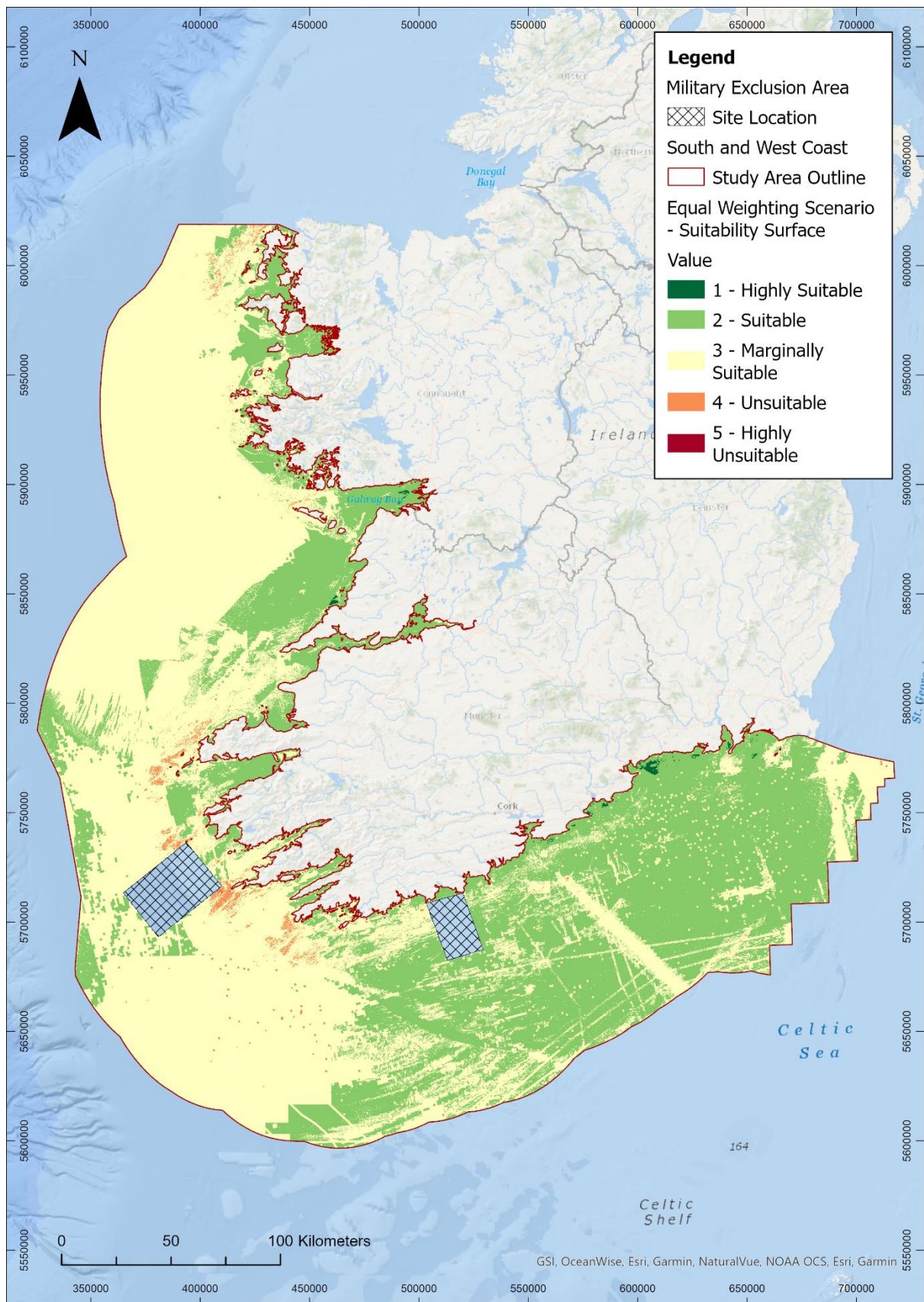


Figure 4.3: Equal Weighting Scenario – Suitability Surface

The South and West Coast totals 62,376 km² in area, when the military exclusion zones are removed. For the Economic Scenario, most of this area (60.11%) is considered “Marginally Suitable”, with “Unsuitable” regions covering 31.05% of the area. This can be accounted for by the lack of existing coastal substations and the exposed bedrock surrounding much of the coastline. Conversely, the parameters set by the Environmental Scenario indicate much higher levels of suitability, with “Suitable” or “Highly Suitable” regions accounting for 68.96% and 23.95% respectively. This can be explained by the widespread distribution of coarse or sandy sediments (see Figure 3.5), with protected or restricted sites comprising a relatively small proportion of the study area. The equal weighting scenario indicates the majority of the area is either “Marginally Suitable” (59.64%) or Suitable (39.43%). For all scenarios, <0.01% of the South and West Coast is considered “Highly Unsuitable”, when all influencing factors are accounted for.

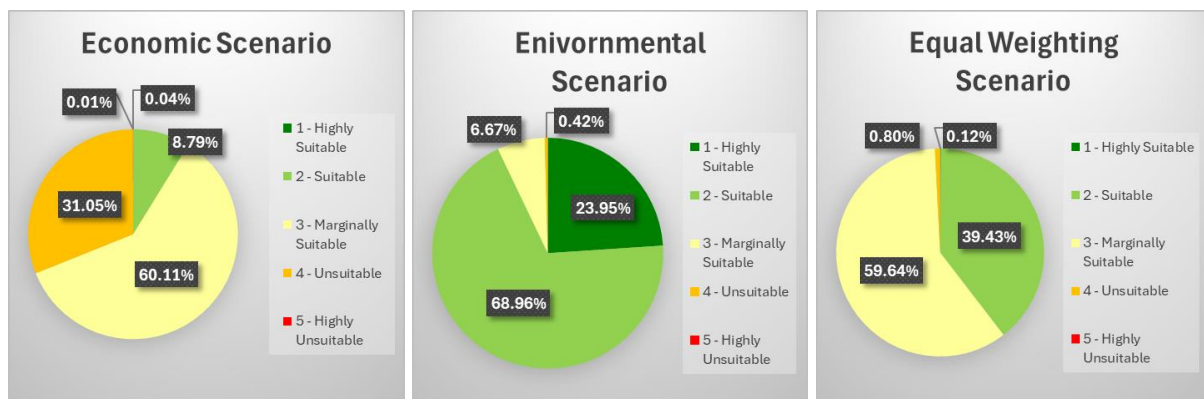


Figure 4.4: Pie Charts representing the percentage of suitability for each scenario

4.2. Site Selection

As detailed in Section 3.8 in the previous chapter, two areas within the South and West Coast have been identified for offshore wind energy development as part of Phases I and II of the Offshore Renewable Energy Support Scheme (ORESS I and II). These areas were selected for analysis using the suitability surfaces described in Section 4.1.

4.2.1. Sceirde Rocks

The Maritime Area Consent issued to the proposed Sceirde Rocks OWF totals approximately 976 km². Table 4.4 below details the resulting suitability values for the Sceirde Rocks project area for each of the three scenarios.

Table 4.4: Results of Site Suitability Analyses - Sceirde Rocks

Economic Scenario			Environmental Scenario			Equal Weighting Scenario		
Value	Area (km ²)	% of area	Value	Area (km ²)	% of area	Value	Area (km ²)	% of area
1	0.31	0.03	1	312.73	32.03	1	12.18	1.25
2	396.52	40.69	2	607.45	62.22	2	581.68	59.58
3	430.52	44.18	3	54.2	5.55	3	380.72	39.00
4	147.15	15.10	4	1.84	0.19	4	1.64	0.17

For the Economic and Equal Weighting Scenario, 84.87-98.58% of the total area is deemed “Suitable” or “Marginally Suitable”. The Economic Scenario indicates 15.10% of the project area is “Unsuitable”, due to exposures of bedrock on the seafloor surrounding the proposed turbine array site. The Environmental Scenario reveals 94.26% of the total area is either “Highly Suitable” or “Suitable”, with the areas deemed less suitable resulting from existing telecommunications cables, reported shipwreck sites and exposed bedrock.

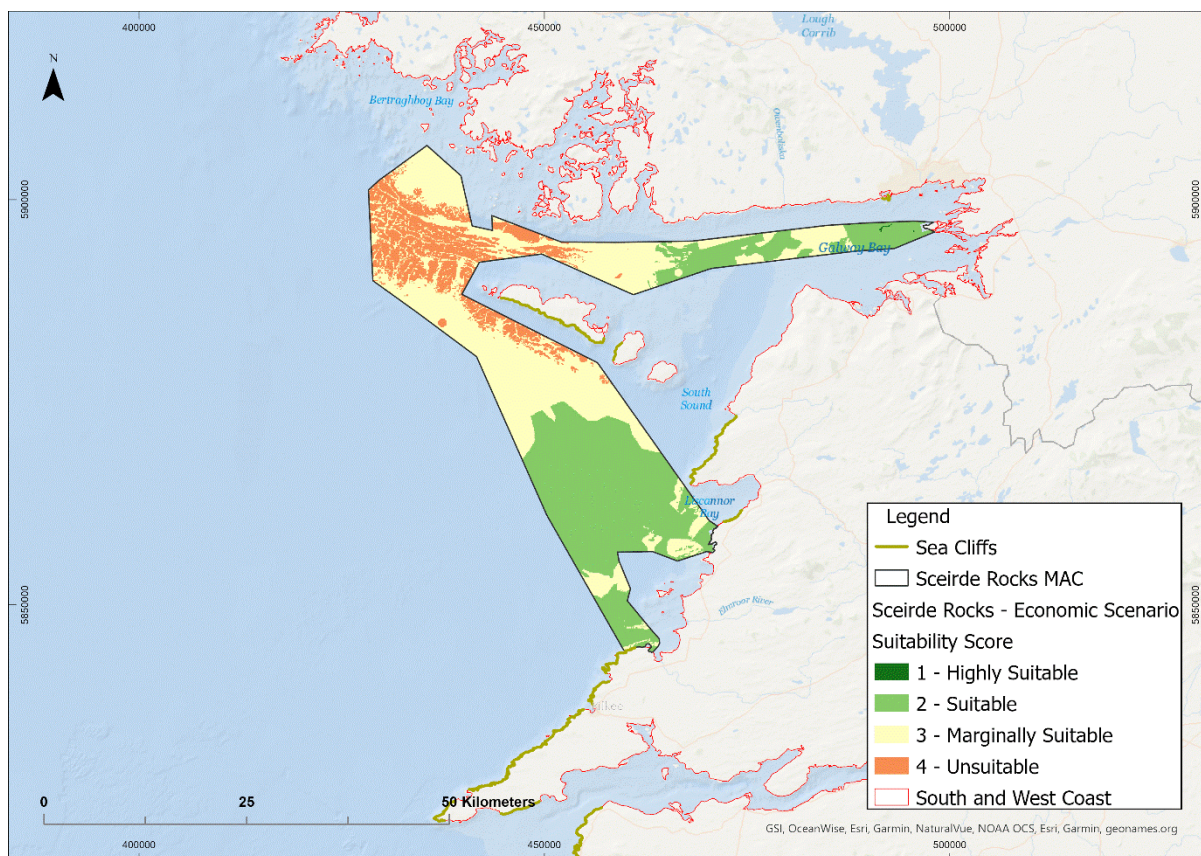


Figure 4.5: Sceirde Rocks Project Area Site Suitability Analysis – Economic Scenario

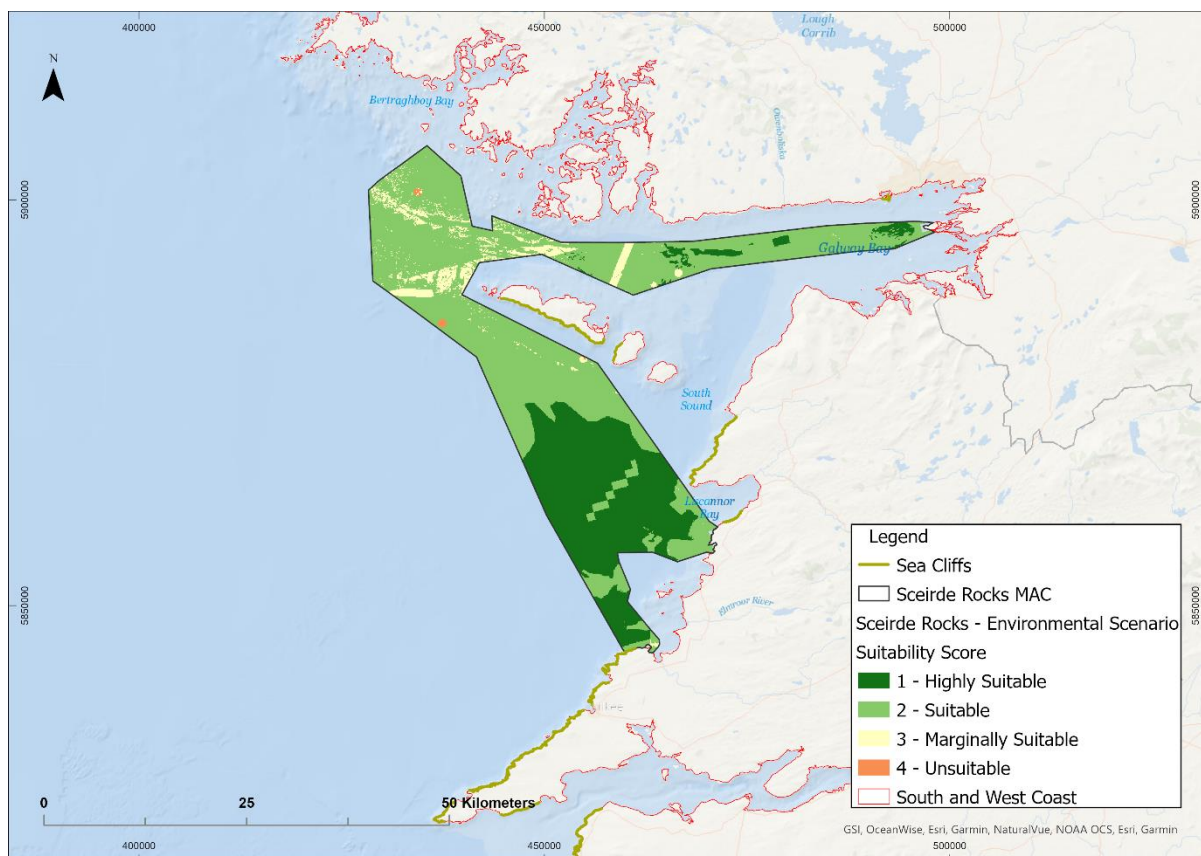


Figure 4.6: Sceirde Rocks Project Area Site Suitability Analysis – Environmental Scenario

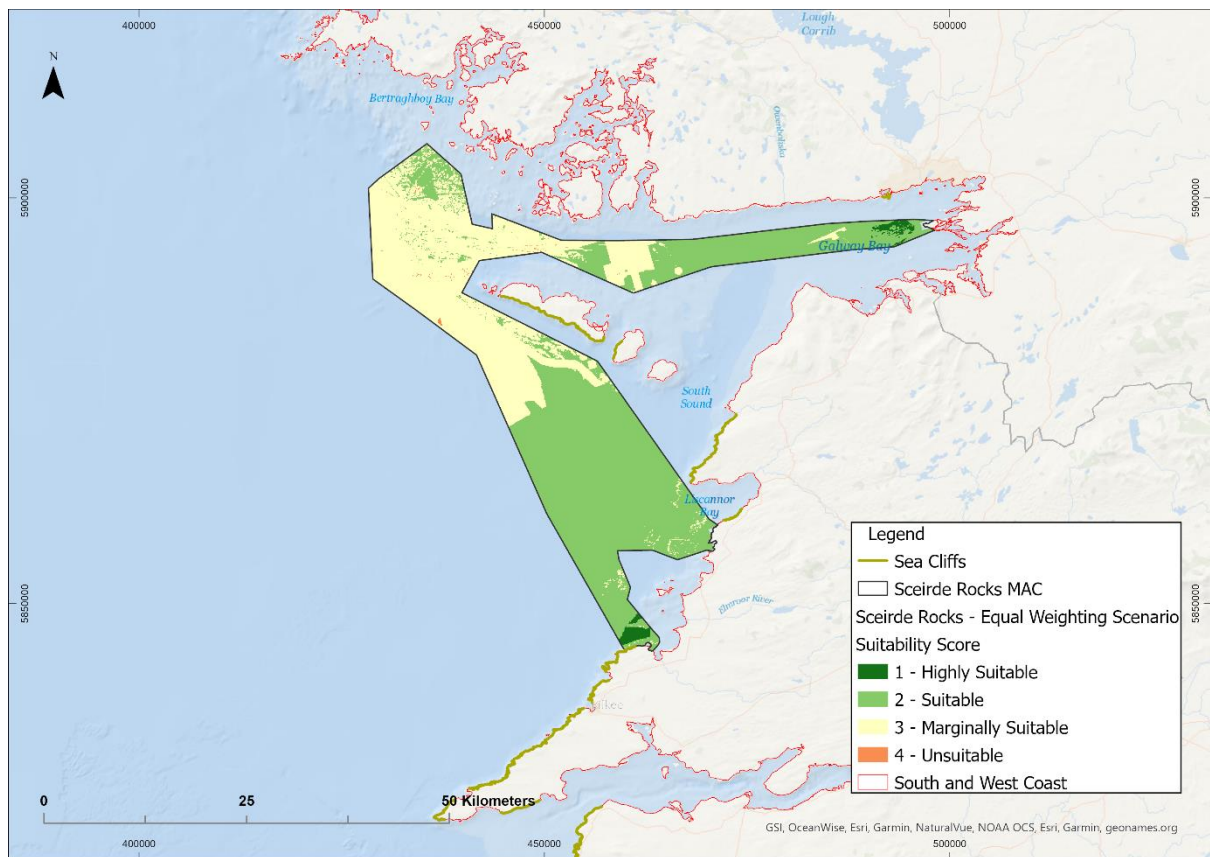


Figure 4.7: Sceirde Rocks Project Area Site Suitability Analysis – Equal Weighting Scenario

4.2.2. South Coast DMAP

The South Coast DMAP is approximately 8,645 km² in area. The resulting suitability values of the total area for SECs, for each of the three scenarios, are shown in Table 4.5 below.

Table 4.5: Results of Site Suitability Analyses- South Coast DMAP

Economic Scenario			Environmental Scenario			Equal Weighting Scenario		
Value	Area (km ²)	% of area	Value	Area (km ²)	% of area	Value	Area (km ²)	% of area
1	15.12	0.17	1	2405.16	27.82	1	56.4	0.65
2	3016.95	34.90	2	5539.05	64.07	2	7310.72	84.57
3	5584.08	64.60	3	630.7	7.30	3	1272.57	14.72
4	28.51	0.33	4	69.75	0.81	4	4.97	0.06

The Environmental Scenario reveals 27.82% of the South Coast DMAP area is “Highly Suitable” with a further 64.07% “Suitable”. The Economic and Equal Weighting Scenarios have <1% total area deemed “Highly Suitable”, with the majority for both scenarios (≥99.29%) classified as either “Suitable” or “Marginally Suitable”. All three scenarios have <1% area which qualifies as “Unsuitable”.

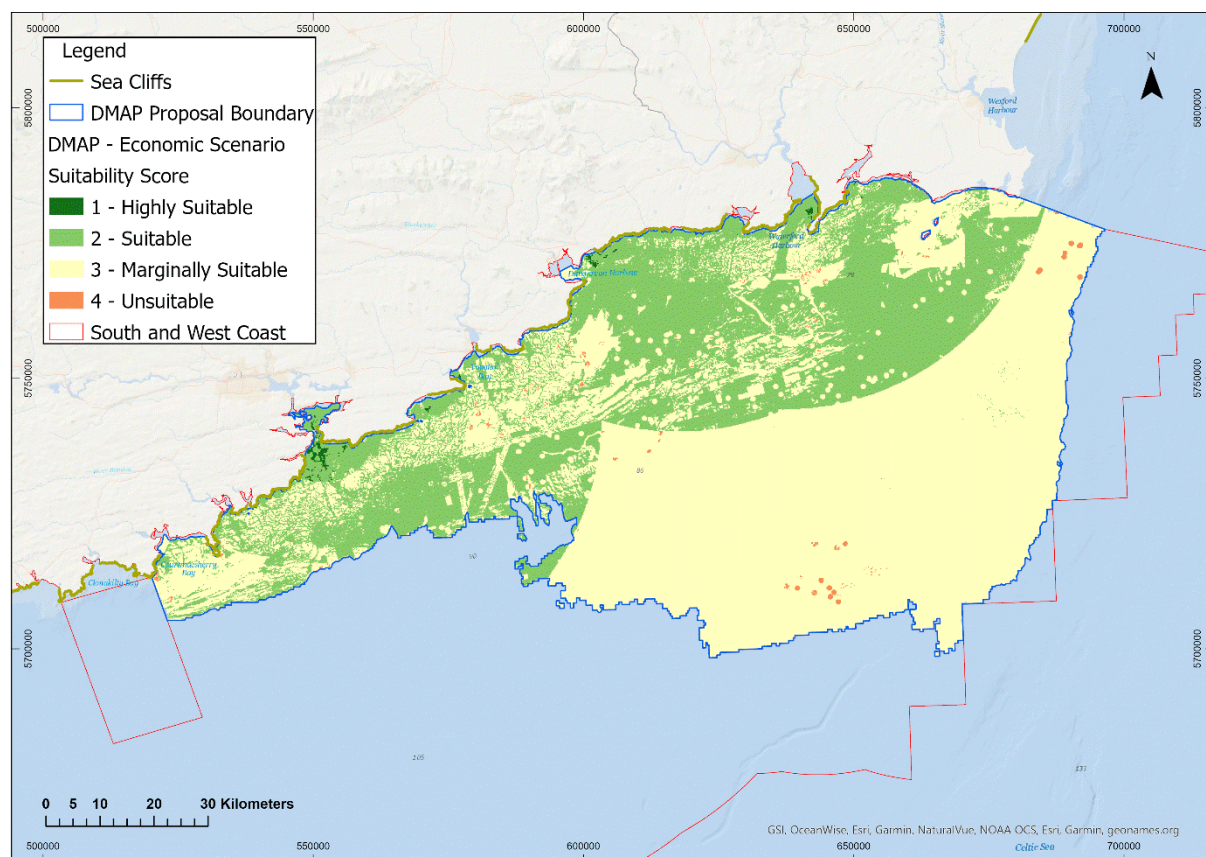


Figure 4.8: South Coast DMAP Site Suitability Analysis – Economic Scenario

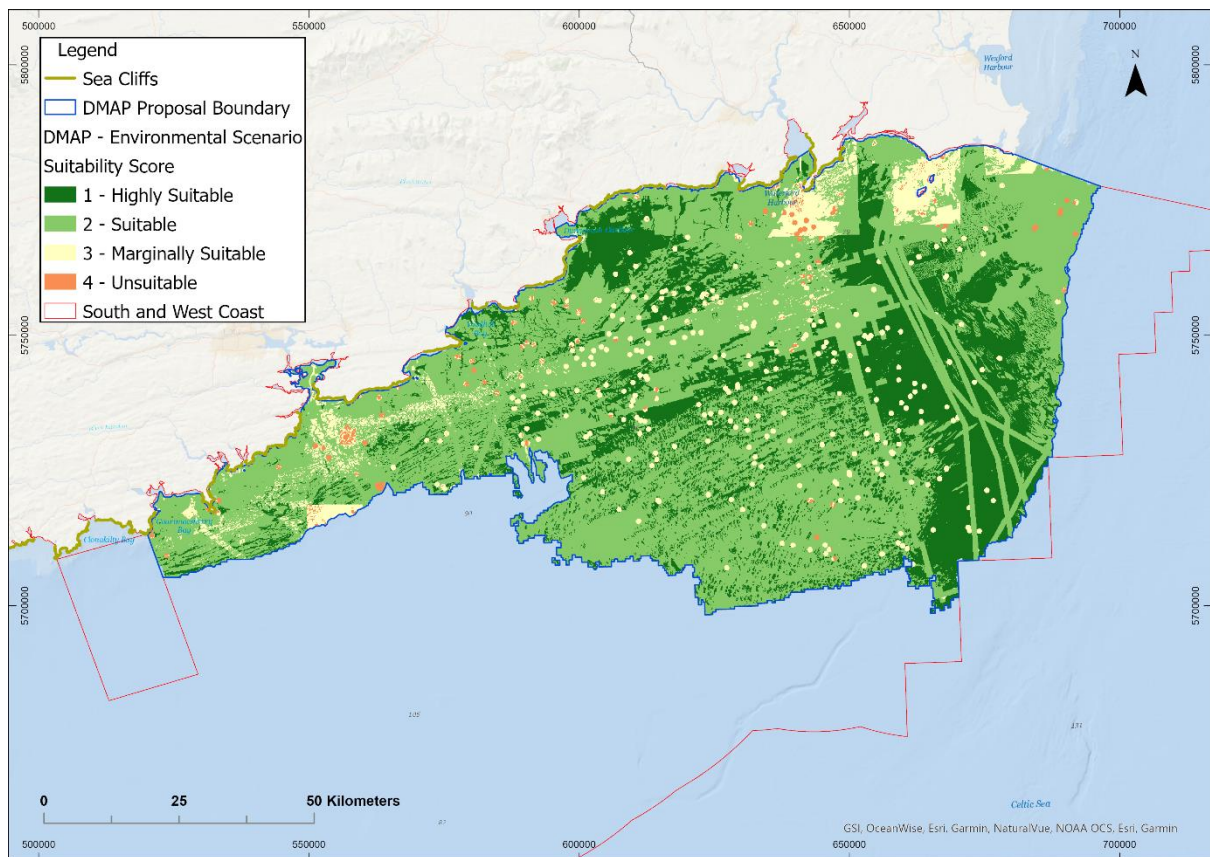


Figure 4.9: South Coast DMAP Site Suitability Analysis – Environmental Scenario

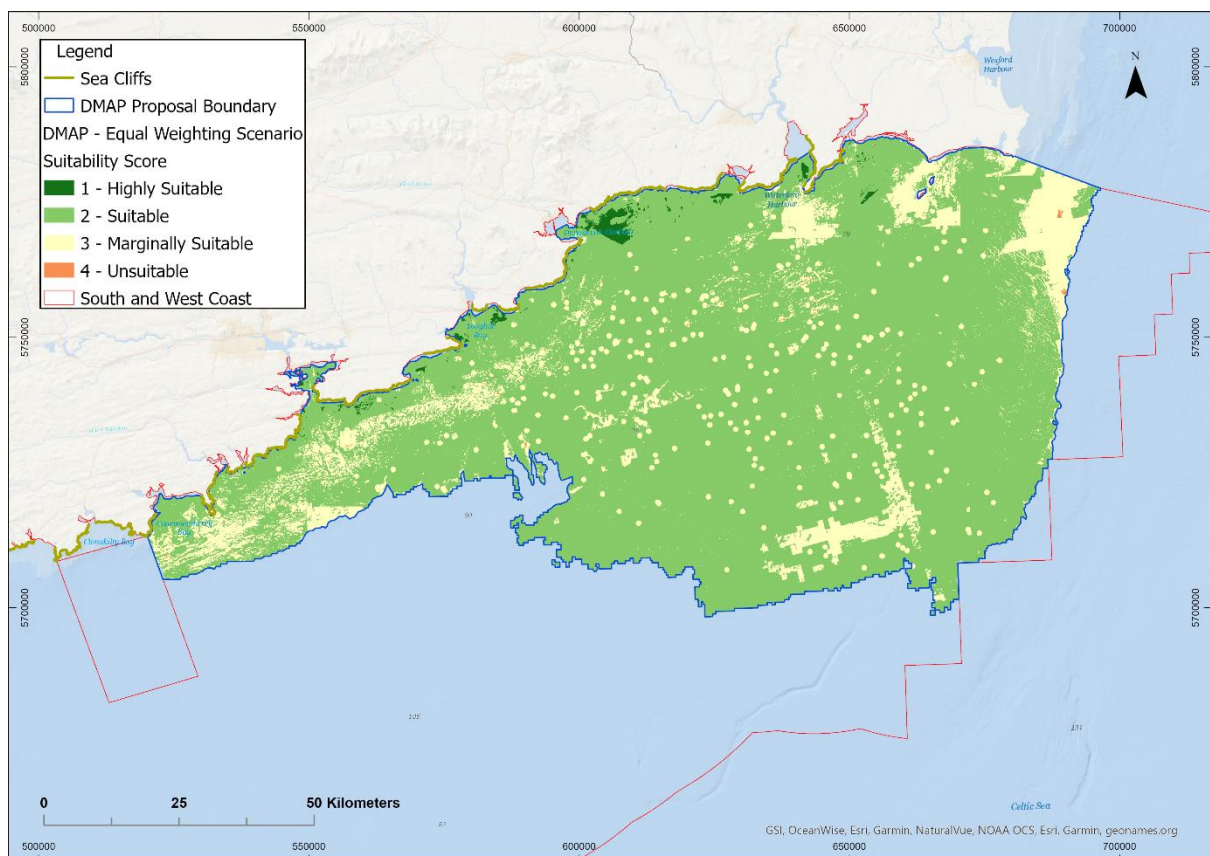


Figure 4.10: South Coast DMAP Site Suitability Analysis – Equal Weighting Scenario

4.3. Route Selection

The LCPA was chosen for producing SEC routes within a GIS (detailed in Section 3.9 in the previous chapter). This was implemented in ArcGIS Pro using the ‘Least Cost Path’ tool and smoothing was applied to the resulting paths. The results for both Sceirde Rocks and the South Coast DMAP sites are discussed below.

4.3.1. Sceirde Rocks

Figure 4.11 below shows the shortest conceivable pathways for three SEC routes between the proposed offshore substation location and the three landfall sites identified within this study.

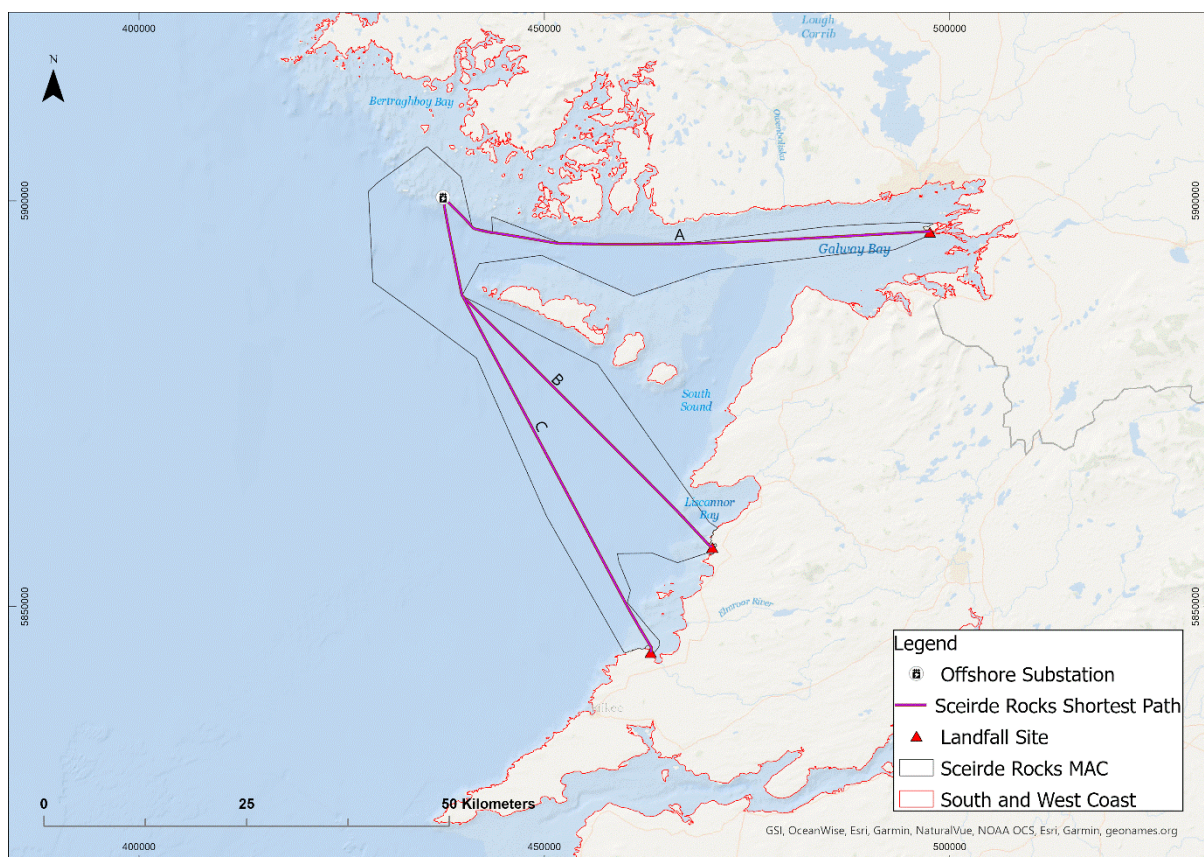


Figure 4.11: Sceirde Rocks - Shortest Routes

Route B is the shortest at 56.06 km, with Route A and Route C totalling 61.87 km and 62.17 km respectively. Figure 4.12 below shows the results for the same three routes, applied over each of the three suitability surfaces.

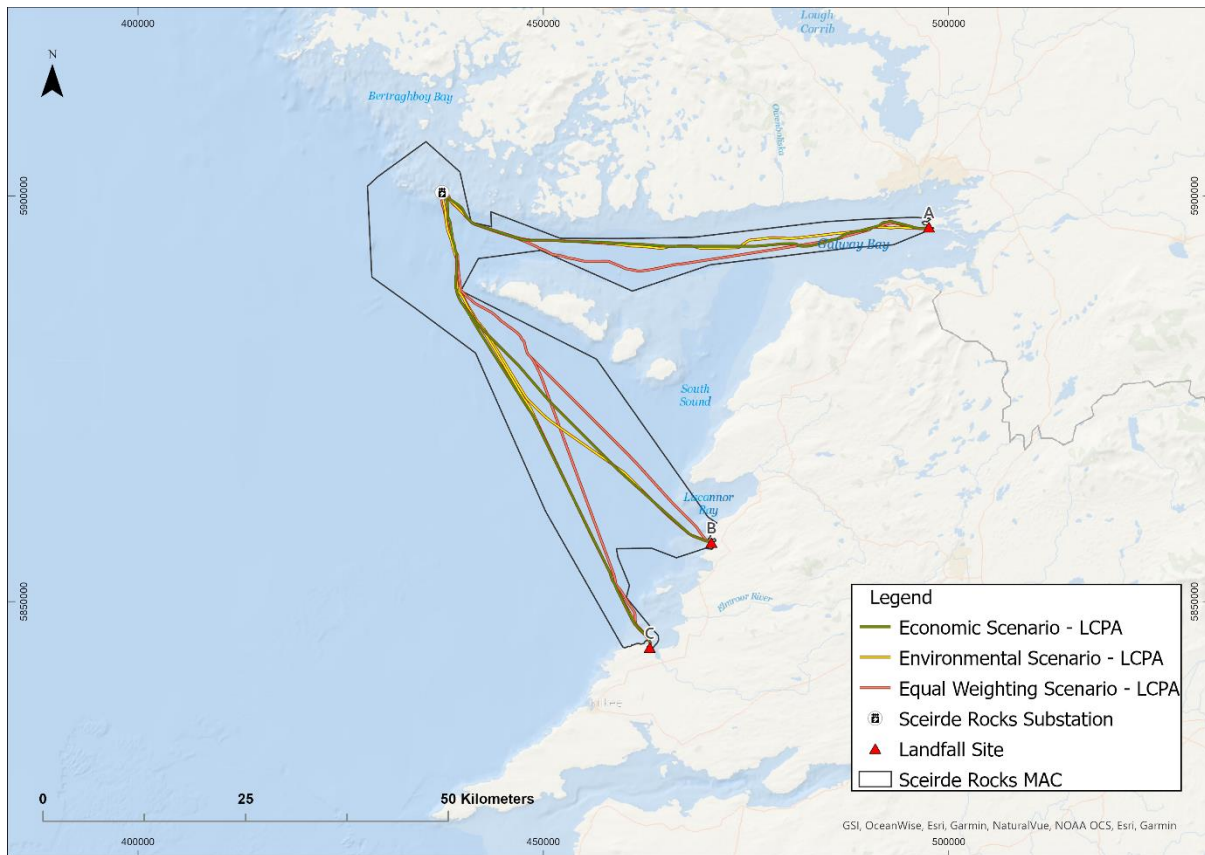


Figure 4.12: Sceilde Rocks – Resulting SEC Routes from LCPA

The routes derived from the LCPA for each of the three scenarios are detailed in Table 4.6 below. Compared to the shortest possible route, all routes are extended by 0.39 to 1.07 km in length, with an average increase of 0.94 km across the three scenarios. Route A is the longest in the Economic and Equal Weighting Scenarios, while Route C is the longest in the Environmental Scenario. Spatially, the Economic Scenario produces routes most similar to the shortest possible routes. The LCPA tends to produce a more complex course for Route A, indicating more variable seabed conditions in this area. Conversely, Route B in the Equal Weighting Scenario and Route C in the Economic Scenario show minimal deviation from the shortest possible routes, suggesting more homogeneous seabed conditions in those regions of the Sceilde Rocks project area.

Route B consistently remains the shortest and has the lowest total associated ‘cost’ for each scenario. The ‘cost’ value reflects the total amount accumulated by each route when traversing every kilometre of a suitability surface, wherein every 100 m cell is weighted by a suitability score ranging from 1 to 5. The ‘Cost-per-km’ value in Table 4.6 below indicates the average value of these cells for every kilometre along a route. Route A has the lowest cost-per-km in the Economic and Equal Weighting Scenario, with this value lowest for Route C in the

Environmental Scenario. When rounded to the nearest whole number, each route tends to cross “Suitable” cells in all three surfaces, except for Routes B and C in the Economic Scenario which tend to pass through “Marginally Suitable” cells.

Table 4.6: Sceirde Rocks - Results of LCPA

Route	Shortest Route	Economic Scenario			Environmental Scenario			Equal Weighting Scenario		
	Length (km)	Length (km)	Route Cost (km)	Cost-per-km	Length (km)	Route Cost (km)	Cost-per-km	Length (km)	Route Cost (km)	Cost-per-km
A	61.87	62.86	156.90	2.50	62.58	109.37	1.75	63.61	140.59	2.21
B	56.06	57.04	149.19	2.62	57.14	88.51	1.55	56.60	132.57	2.34
C	62.17	62.68	161.74	2.58	62.56	94.48	1.51	63.70	144.39	2.27

The results for the Sceirde Rocks project area indicate that all three routes could be considered suitable depending on the concerns of the decision maker. Although Route B is the shortest, its high cost-per-km value in the Economic and Equal Weighting Scenarios reflects the fact that its landfall site is the furthest from a suitable existing grid connection point. Conversely, Route A, despite being the longest on average, has the lowest cost-per-km in these scenarios due to its relative proximity to a coastal substation. Route C has the lowest cost-per-km in the Environmental Scenario, however given the Sceirde Rocks Project is currently in development, and therefore must utilise existing grid infrastructure, this scenario is less appropriate. Based on this assessment, Route A from the Economic Scenario would appear to be the most optimal SEC route, with Route C from the same scenario serving as a viable alternative.

4.3.2. South Coast DMAP

Figure 4.13 below shows the shortest possible routes from a series of potential offshore substation locations placed at 1 km intervals at the 12 nm limit, resulting in 118 individual points. The closest potential substation to each of the twenty proposed landfall sites was calculated, with the intermediate paths discarded. The landfall sites were placed at potentially suitable locations along the northern boundary of the South Coast DMAP, extending from Myrtleville, Co. Cork in the west to Carnsore Point, Co. Wexford in the east.

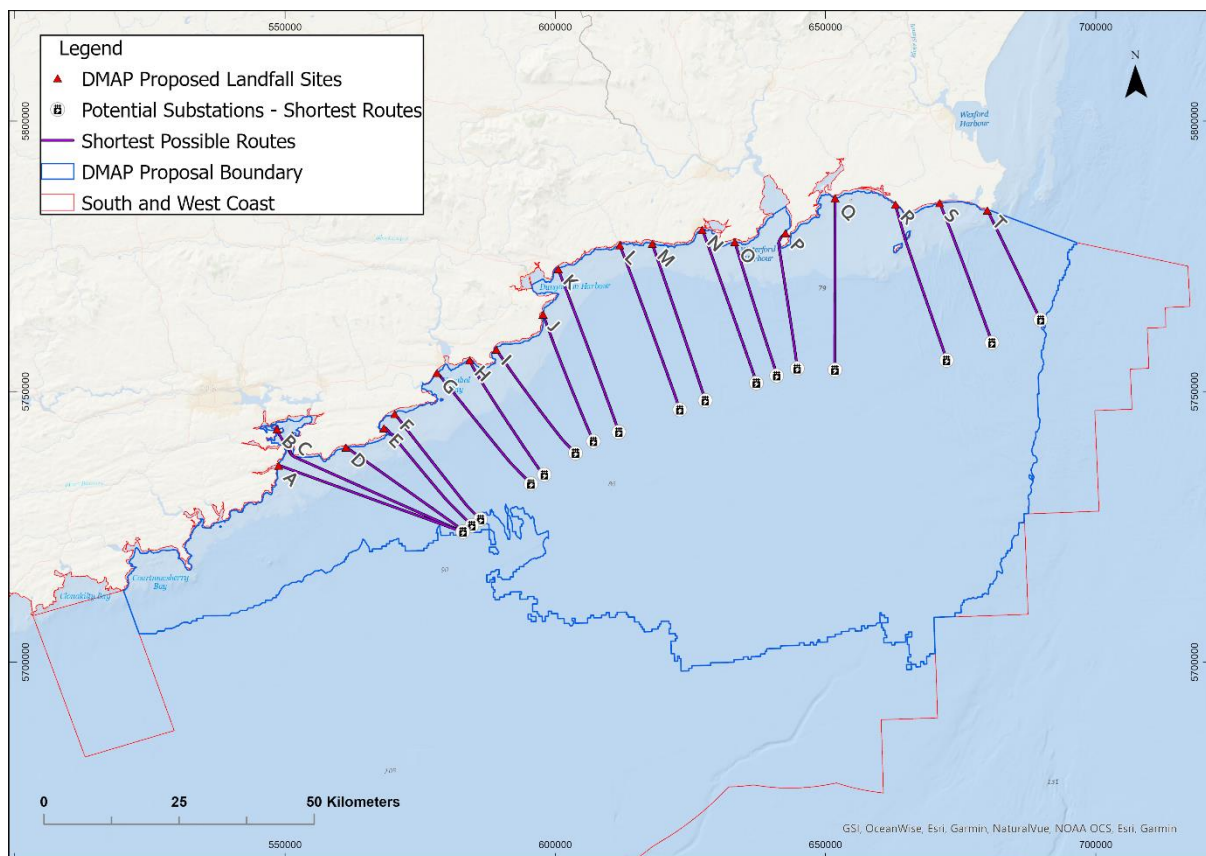


Figure 4.13: South Coast DMAP – Shortest Routes

The twenty routes range in length from 22.53 km (Route T) to 40.29 km (Route B). The five shortest routes overall are Routes T, I, E, F, and H. While all suggested offshore substations were positioned along the 12 nm limit (detailed in Section 3.8), it is important to note that this limit is measured from a baseline – a simplified representation of the coastline. Consequently, landfall sites situated in indented coastal regions, between headlands, are farther away from the 12 nm limit in total distance. Figure 4.14, Figure 4.15, and Figure 4.16 below show the resulting routes derived from the LCPA for each of the three scenarios.

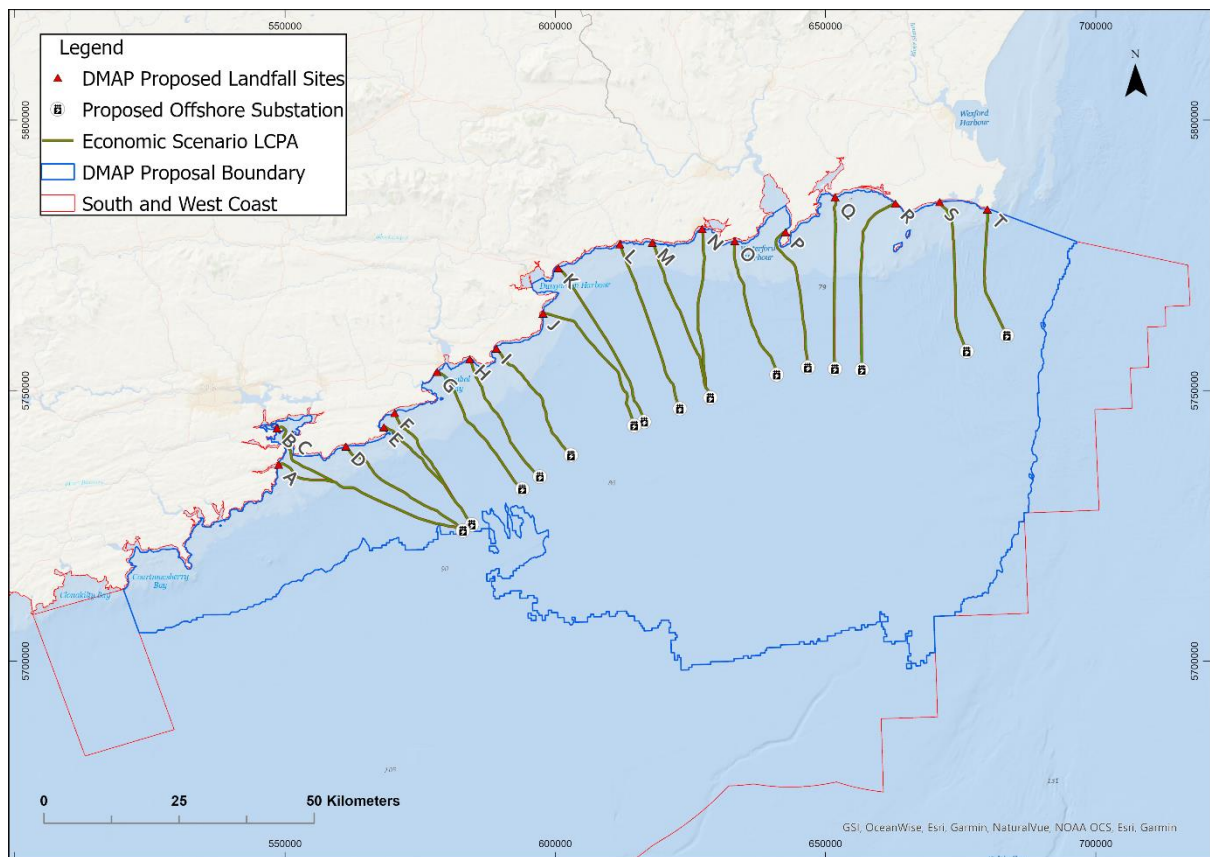


Figure 4.14: South Coast DMAP – Economic Scenario LCPA Results

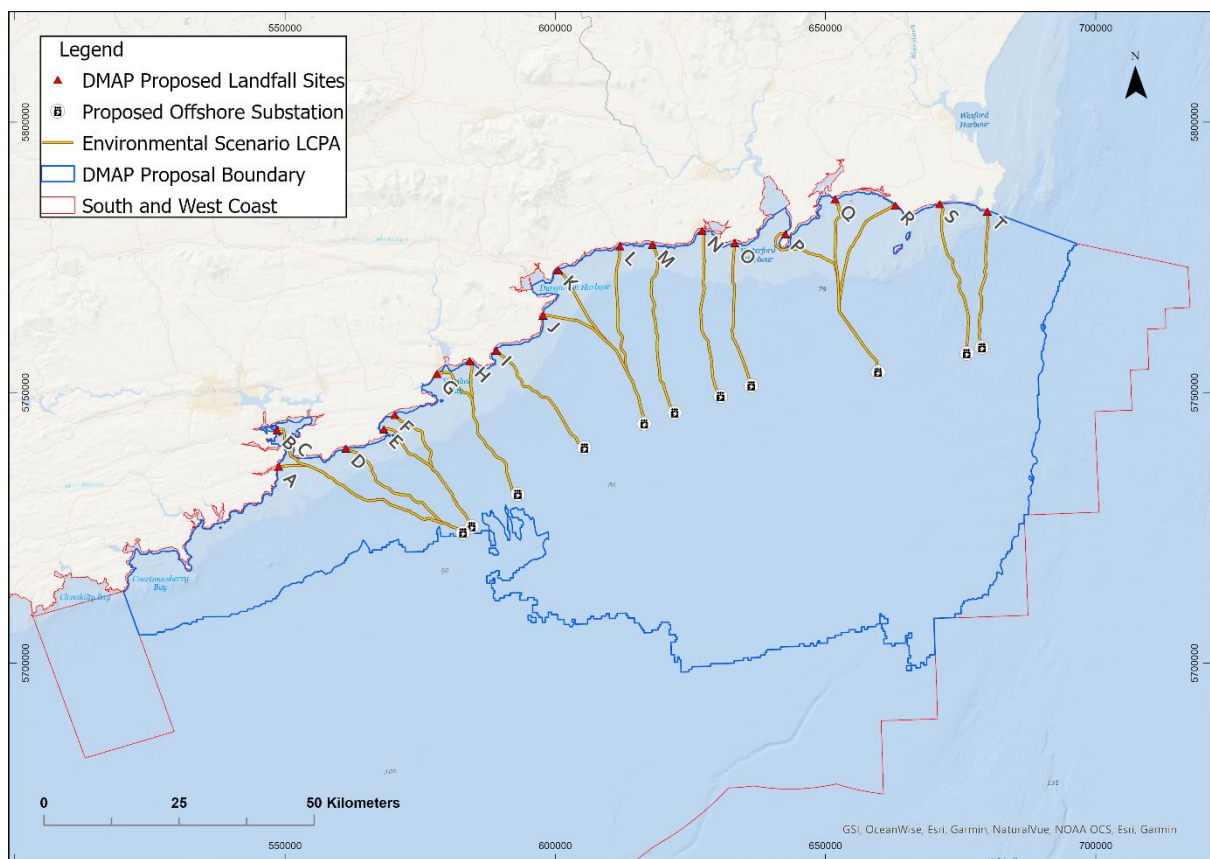


Figure 4.15: South Coast DMAP – Environmental Scenario LCPA Results

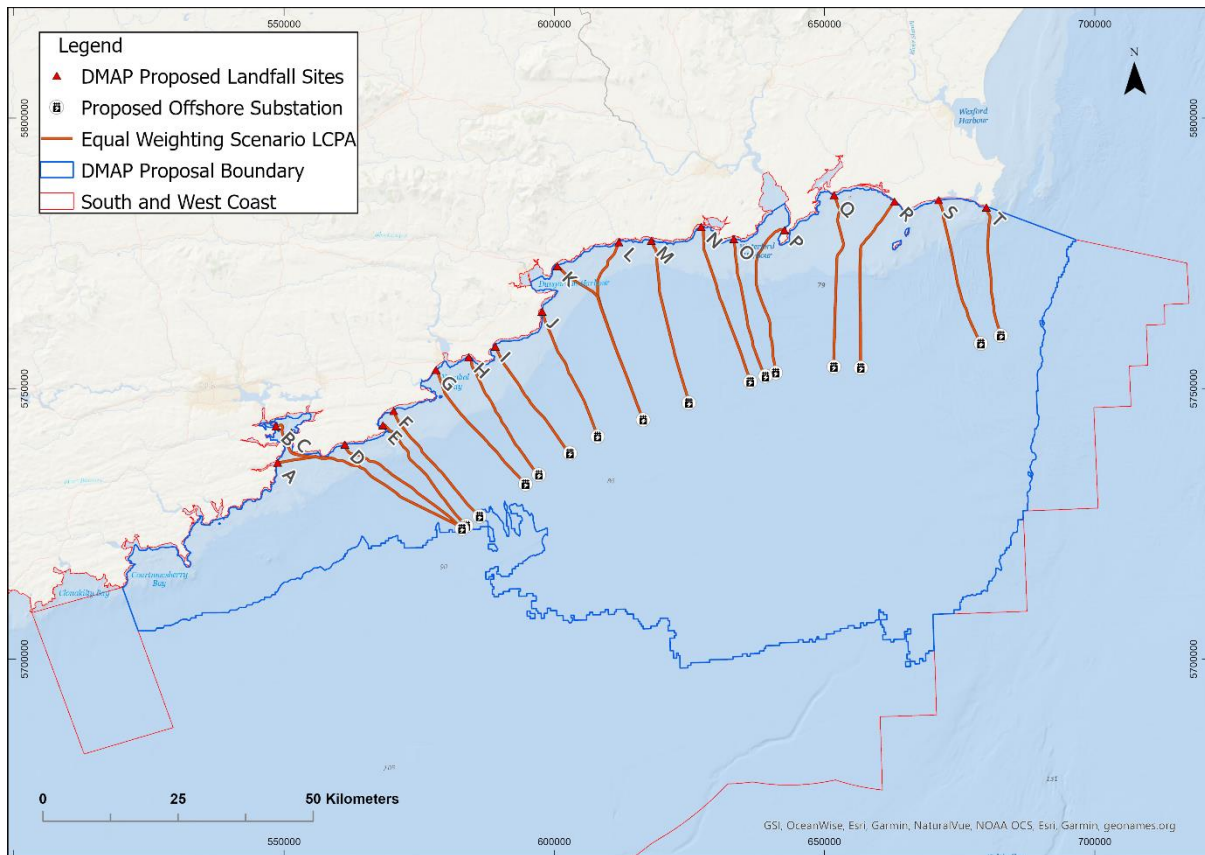


Figure 4.16: South Coast DMAP – Equal Weighting Scenario LCPA Results

The resulting routes derived from the LCPA are increased in length by 0.10-11.97 km, when compared with the shortest possible length for each route. Routes are increased, on average, by 1.13 km in the Economic Scenario, 2.82 km in the Environmental Scenario and 1.05 km in the Equal Weighting Scenario. Route T remains the shortest overall in the Economic and Equal Weighting Scenario, with Route E the shortest in the Environmental Scenario. Route B remains the longest route throughout.

The associated cost of each route is more variable. For the Economic Scenario, the five routes with the lowest associated cost are Routes F, E, I, H and G. In the Environmental Scenario these routes are, Routes H, Q, G, I, and J and for the Equal Weighting Scenario these are Routes I, H, E, F and J. Table 4.7 below provides a detailed view of the results of the LCPA for each scenario within the South Coast DMAP.

Table 4.7: Results of LCPA - South Coast DMAP

Route	Shortest Route	Economic Scenario			Environmental Scenario			Equal Weighting Scenario		
	Length (km)	Length (km)	Route Cost (km)	Cost-per-km	Length (km)	Route Cost (km)	Cost-per-km	Length (km)	Route Cost (km)	Cost-per-km
A	36.23	37.18	71.90	1.93	37.75	61.03	1.62	37.94	72.55	1.91
B	40.29	42.43	81.11	1.91	42.40	72.25	1.70	42.05	81.08	1.93
C	38.72	40.02	77.92	1.95	40.08	67.77	1.69	39.72	77.49	1.95
D	26.78	27.31	57.02	2.09	28.44	43.51	1.53	27.42	54.11	1.97
E	24.43	24.73	52.73	2.13	25.51	42.28	1.66	24.63	50.34	2.04
F	25.24	25.53	52.64	2.06	26.80	42.73	1.59	25.41	50.42	1.98
G	26.97	27.31	56.90	2.08	29.95	38.67	1.29	27.26	53.22	1.95
H	25.32	25.83	56.67	2.19	28.02	35.80	1.28	25.64	49.28	1.92
I	24.20	25.03	55.48	2.22	25.59	38.95	1.52	24.30	48.55	2.00
J	25.36	28.97	60.01	2.07	30.28	39.04	1.29	25.48	51.42	2.02
K	32.10	32.88	64.51	1.96	33.17	41.08	1.24	33.68	58.33	1.73
L	32.44	32.58	66.41	2.04	34.17	43.37	1.27	35.54	63.80	1.80
M	30.69	31.02	63.53	2.05	32.80	42.61	1.30	31.05	61.59	1.98
N	30.00	31.80	64.86	2.04	31.67	50.00	1.58	30.26	59.96	1.98
O	25.99	26.58	56.94	2.14	27.33	50.45	1.85	26.34	53.26	2.02
P	25.78	27.51	62.14	2.26	37.75	56.05	1.48	29.54	59.55	2.02
Q	31.78	31.88	63.90	2.00	35.16	36.87	1.05	32.58	60.80	1.87
R	30.32	33.79	68.66	2.03	37.42	44.62	1.19	32.85	66.13	2.01
S	27.64	28.78	63.12	2.19	29.30	39.10	1.33	27.87	56.27	2.02
T	22.53	24.36	61.43	2.52	25.71	43.27	1.68	24.22	52.97	2.19

The cost-per-km values for each route across the three scenarios are also variable. The five routes with the lowest cost-per-km are Routes B, A, C, K and Q in the Economic Scenario, Routes Q, R, K, L and H in the Environmental Scenario and Routes K, L, Q, A and H in the Equal Weighting Scenario. The results for this value in the Economic Scenario highlight that although Routes B, C and A are the longest overall with the highest cost, they have the lowest cost-per-km values, indicating these routes are positioned in more suitable locations on average. Conversely, for the Economic and Equal Weighting Scenarios, Route T is the shortest route overall but has the highest cost-per-km value.

As with the example of Sceirde Rocks, the optimised SEC routes produced by the LCPA for the South Coast DMAP region will vary depending on the judgments of the decision maker. For example, Routes C, B, and A score highly for the Economic and Equal Weighting Scenarios, given the presence of several suitable grid connection points surrounding Cork City, adjacent to those routes' landfall sites. The same routes score poorly for the Environmental Scenario, due to the presence of exposed bedrock and a busy marine vessel route within, and surrounding, Cork Harbour.

Some routes score highly across all three scenarios, highlighting two key areas within the South Coast DMAP which are deemed highly suitable for SEC routes. These areas contain some of the lowest overall cost and the lowest cost-per-km routes (see Figure 4.18 below). These

regions are termed DMAP_Waterford and DMAP_Wexford. The sediment thickness was analysed for these two areas using the available SBP data to further optimise SEC routing.

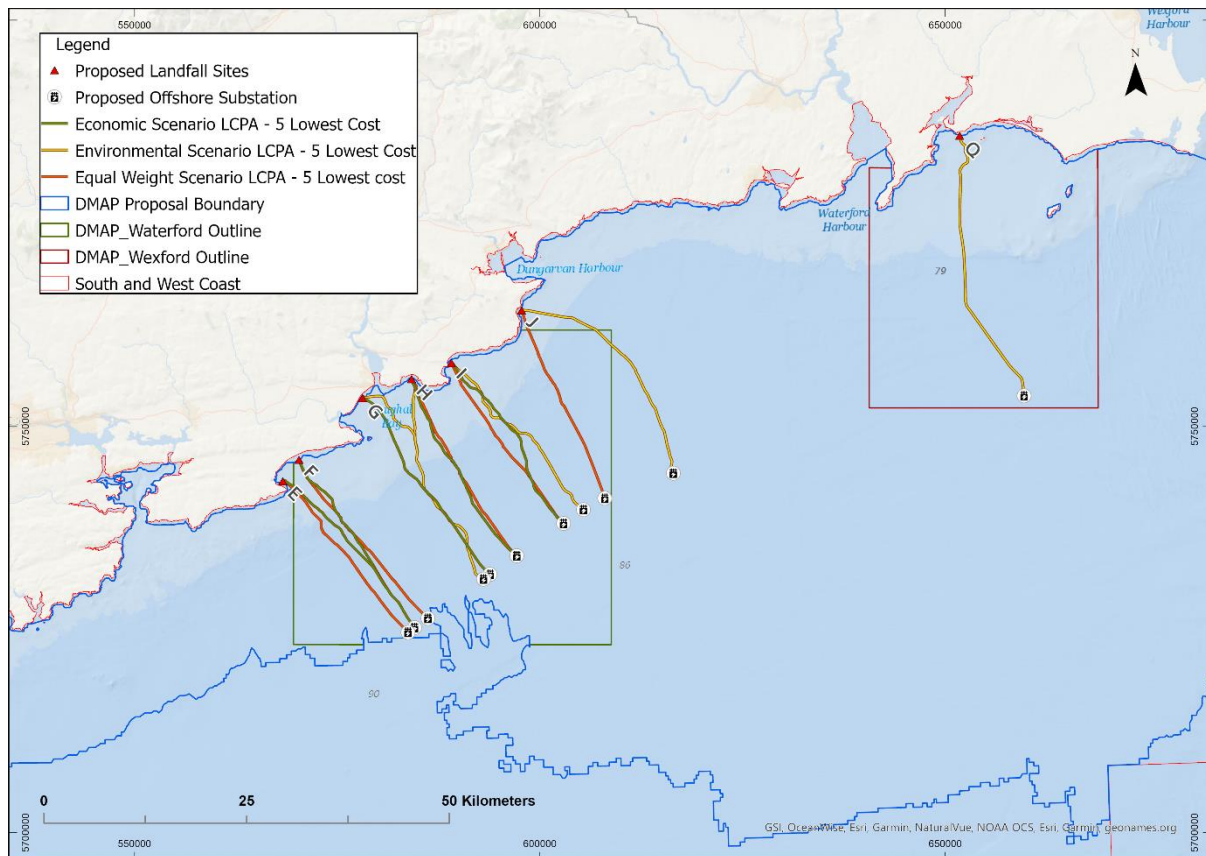


Figure 4.17: South Coast DMAP – Top Five Lowest Overall Cost Routes for each Scenario

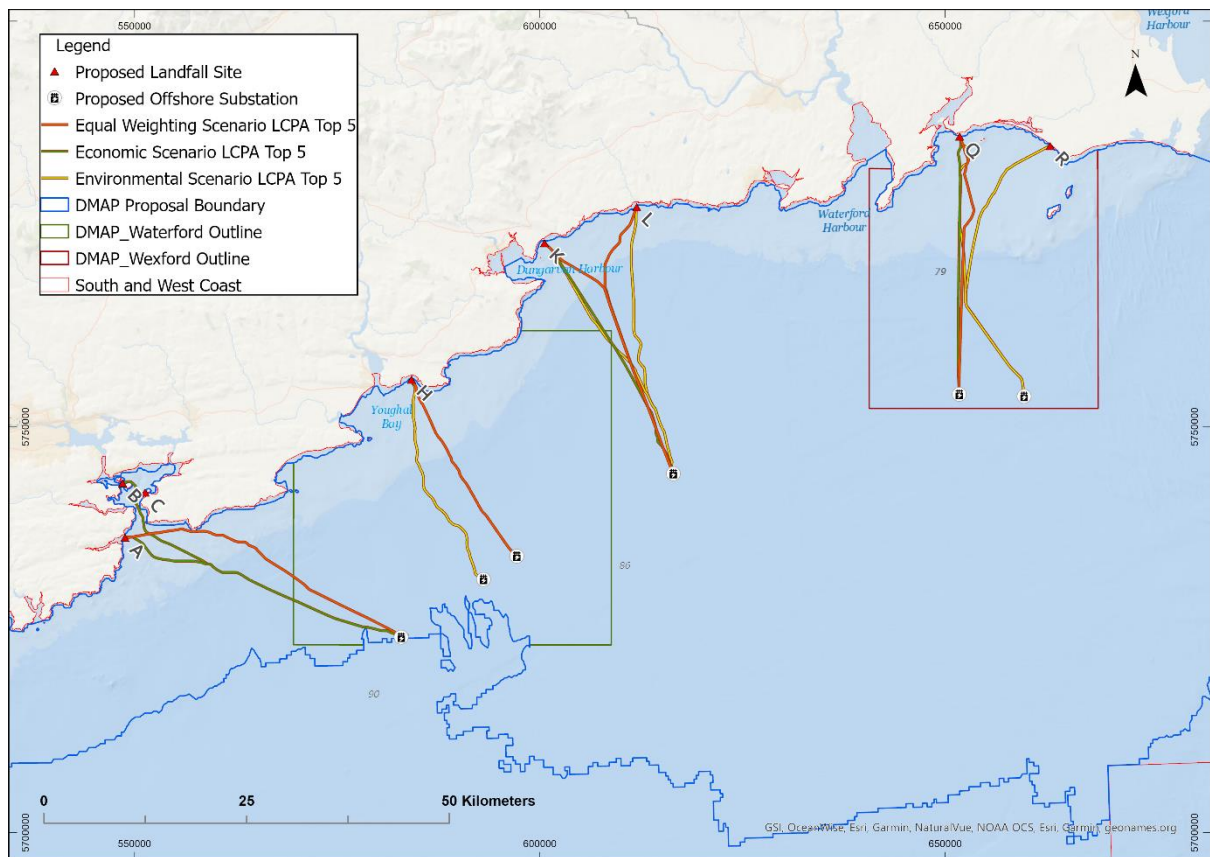
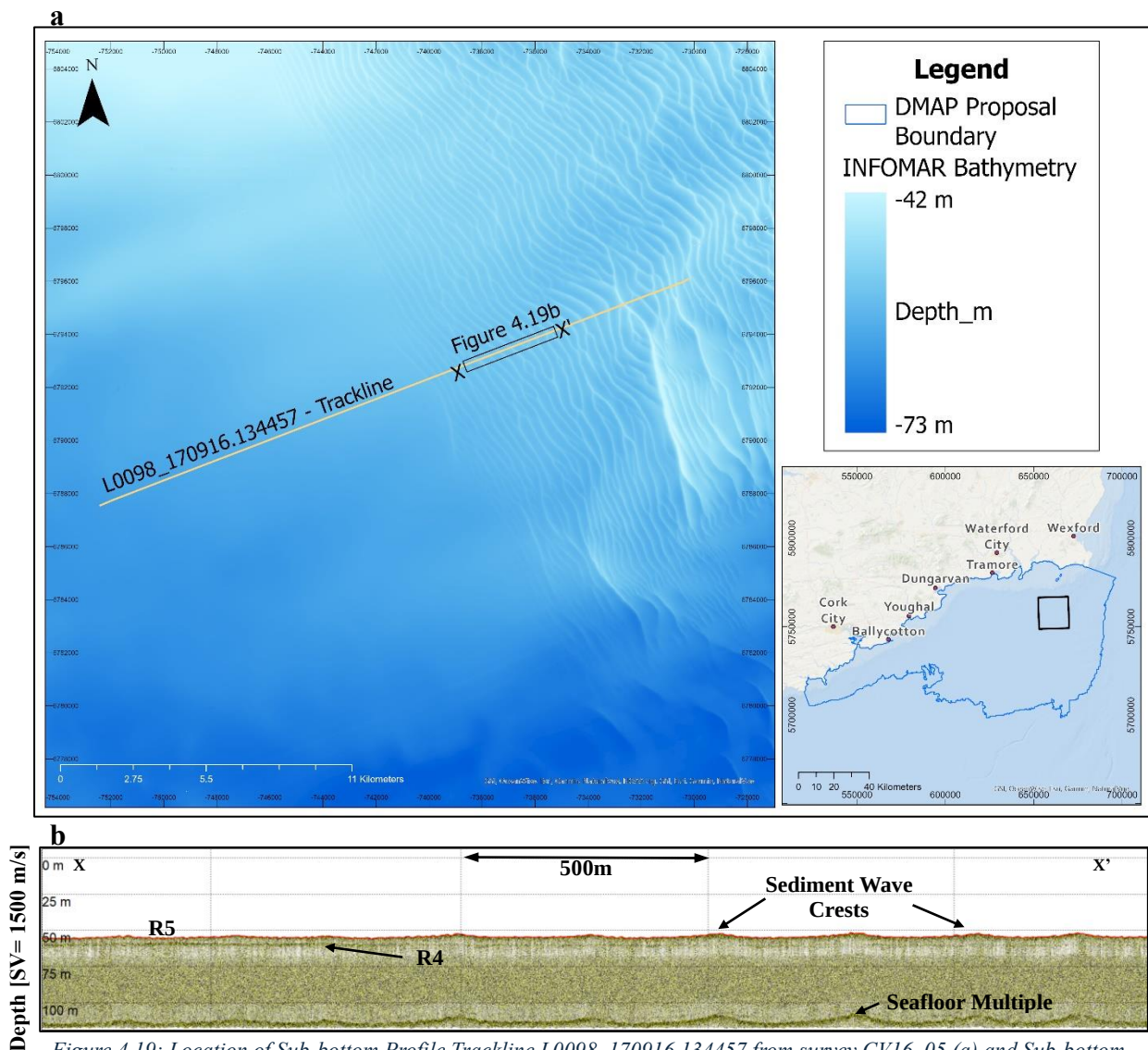


Figure 4.18: South Coast DMAP – Top Five Lowest cost-per-km Routes for each Scenario

4.4. Sub-bottom Profile Analysis

A total of 506 SBP lines from the INFOMAR (2022) dataset were fully, or partially, processed in this study for the DMAP_Waterford and DMAP_Wexford areas (shown above in Figure 4.17 and Figure 4.18). This consisted of a series of lines from seven INFOMAR surveys; CV07_02, CV10_02, CV10_03, CV12_03, CV13_01, CV16_01 and CV16_05 (INFOMAR, 2022) Each line was analysed to determine the potential thickness of seafloor sediment. Individual reflectors (R) and morphological features within the two areas were also identified, resulting in the four Seismic Units (SU) which were defined during processing, examples of which are shown below.



SU4 is classified as the uppermost sedimentary unit, expressed as low-amplitude, parallel layers. Its thickness is measured from the base of the unit (R4) to the seafloor surface (R5) (Figure 4.19). SU4 is the most frequently observed layer in the dataset, especially within DMAP_Wexford where it is visible throughout much of the data. Sediment samples conducted by INFOMAR (2023d) in areas underlain by SU4, indicate this unit can be categorized as sand, gravelly sand or sandy gravel. In the southeastern regions of DMAP_Wexford, SU4 exhibits large scale, sediment wave morphologies, indicative of sediment mobility in this area. Analysis of the sediment thickness data reveals this unit has an average thickness of 2.51 m with a maximum thickness of 12.55 m in DMAP_Waterford and an average thickness of 4.16 m with a maximum thickness of 10.25 m in DMAP_Wexford.

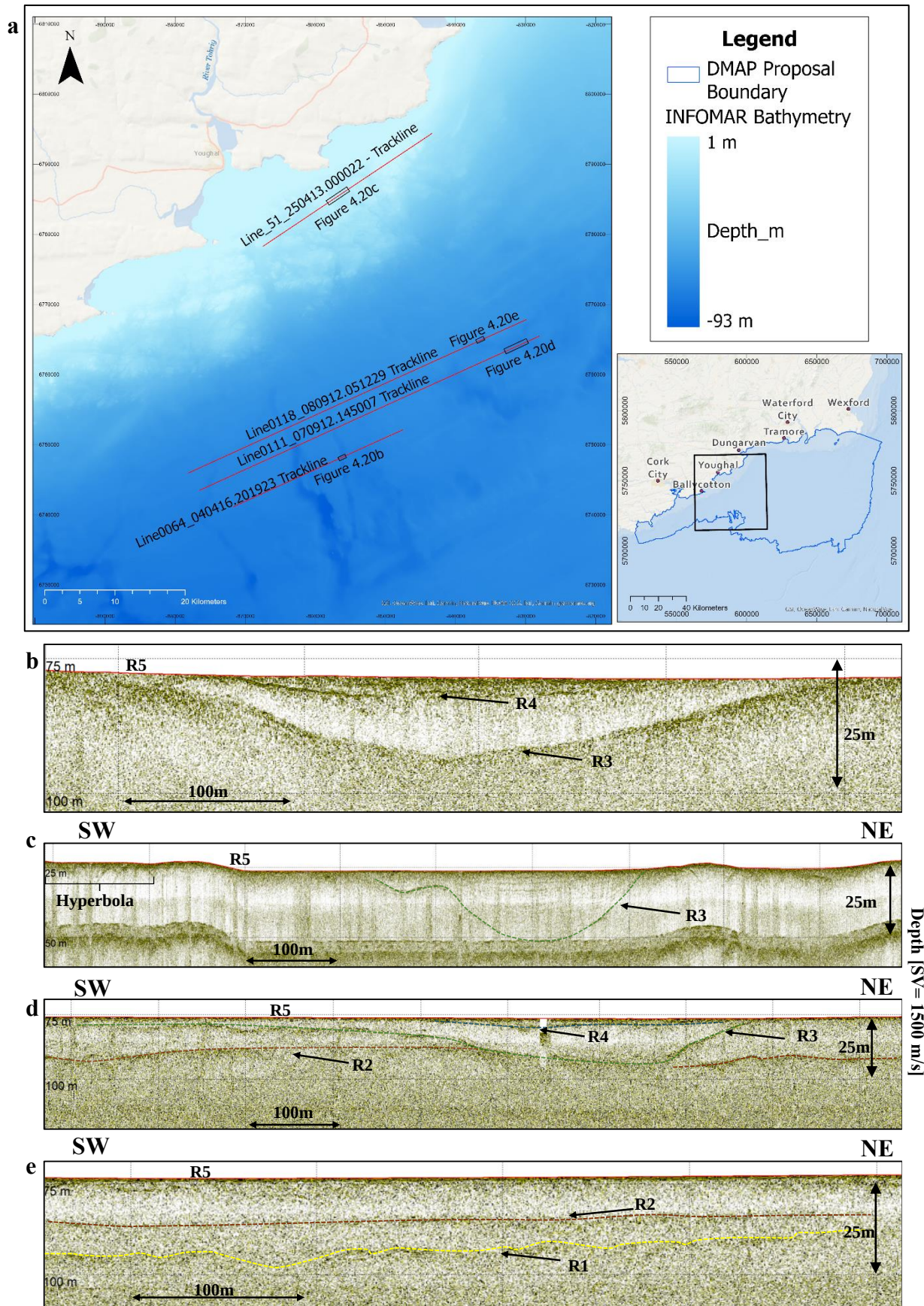


Figure 4.20: Location of Sub-bottom Profile Tracklines (a) and Sub-bottom Profile views (3X Vertical Exaggeration) with examples of Seismic Reflectors R3 and R4 (b), Digitised Seismic Reflector R3 with Hyperbola Corresponding with Outcropping Bedrock (c), Digitised Seismic Reflectors R2, R3 and R4 (d), and Digitised Seismic Reflectors R1 and R2 (e)

SU3 is defined as the sediment infilling a channel (R3) along the seafloor, where the eastern and western banks, or walls, of the channel are clearly visible (Figure 4.20b, Figure 4.20c). The top few metres of these channels are often infilled by a thin layer of SU4 type sediments. Internal SU3 reflectors reveal faint layering of sediments conforming to the shape of the channel, indicative of the infilling nature of this unit. SU3 reaches a maximum observable thickness of 28.85 m in DMAP_Waterford and 17.45 m in DMAP_Wexford.

R2 is the lowest identifiable layer of sediment within the SBP data. Generally, it is somewhat irregular in appearance, occurring below R4 in the profile and sometimes incised by a paleochannel (R3) (Figure 4.20d). R1 is interpreted as the buried surface of the bedrock, or possibly the surface of a glacial till deposit (Figure 4.20e). R1 is irregular and hummocky in appearance with numerous high-amplitude, hyperbolae, which form within SBP datasets when the passing acoustic signal reflects off hard objects such as a buried pipeline, a boulder or bedrock (Zheng *et al.*, 2021). No reflectors are seen below R1 and given the relatively low penetration depths achievable by the ‘pinger’ profiler system, R1 is not frequently observed in the data. SU1 and SU2 are the seismic units measured from the top of R1 or R2, respectively, to the seafloor. These reach a maximum thickness of 39.52 m in DMAP_Waterford and 23.47 m in DMAP_Wexford.

After computing the thickness of the individual units in SonarWiz, the resulting point data was imported into ArcGIS for interpolation using the EBK method described in Section 3.10 of the previous chapter. For many individual point locations, several units may be present and overlapping. For the purposes of this study, the highest thickness value present for each unit was used for interpolation. It should be noted that this value does not represent depth to bedrock, which in most cases is not clearly visible in the data. Instead, this value is the maximum *identifiable* thickness of sediment for any given point within the interpolated areas.

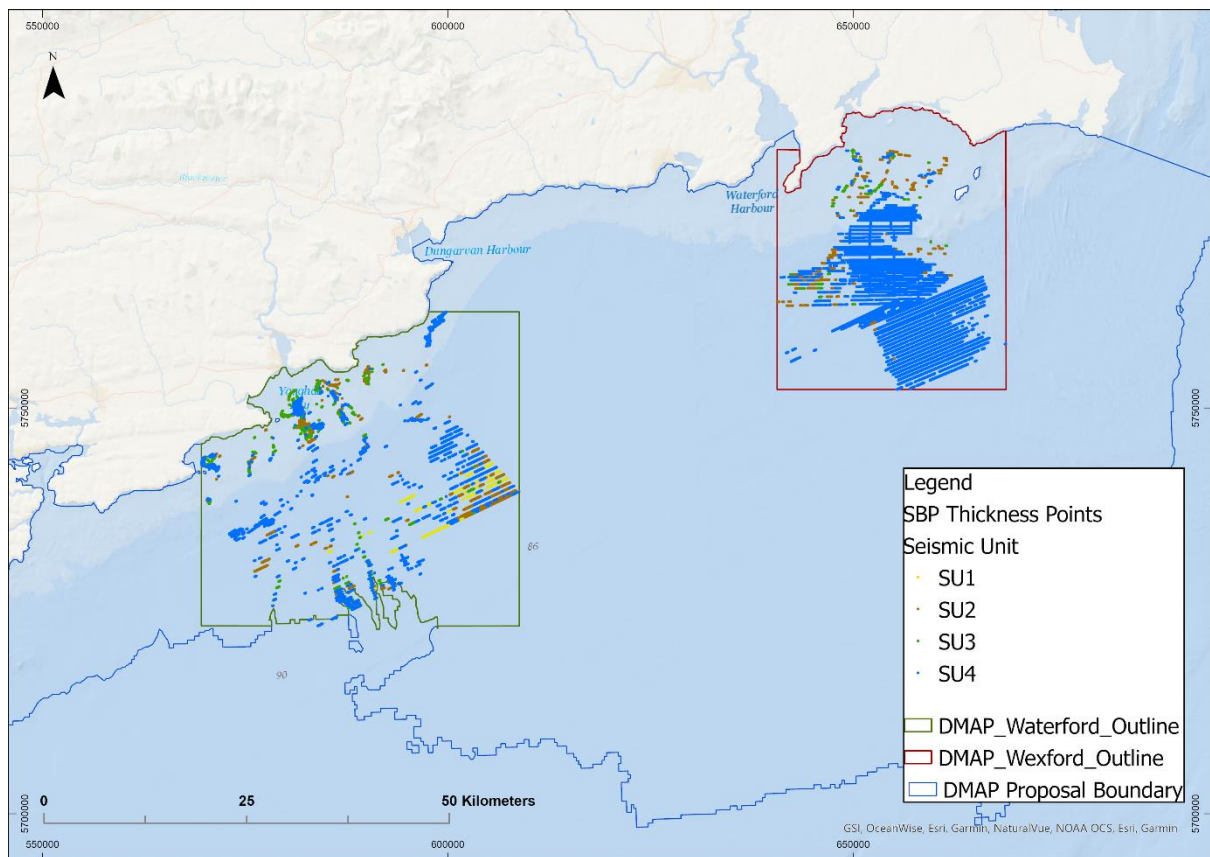


Figure 4.21: Seismic Unit Thickness Point data

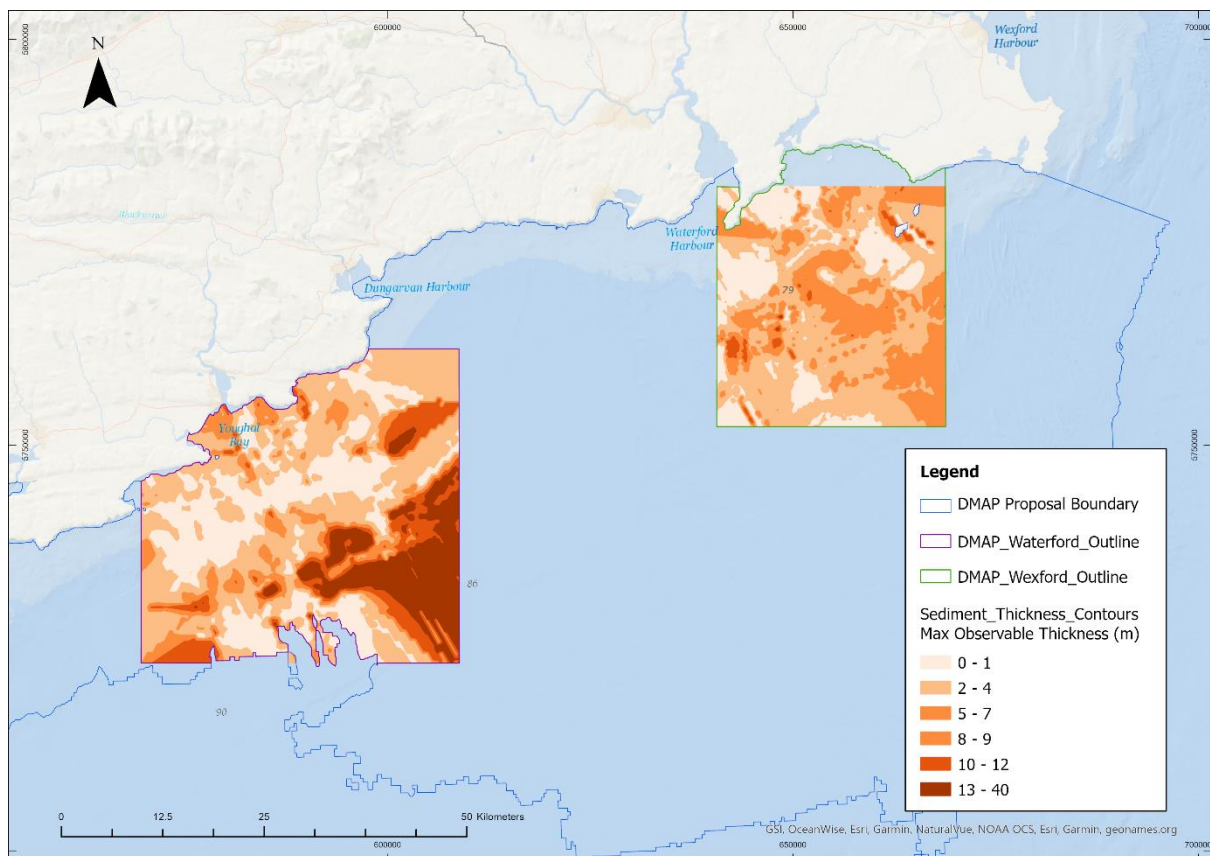


Figure 4.22: South Coast DMAP - EBK Interpolation Grids

The outer boundaries of the interpolated grids were clipped to the South Coast DMAP outline and areas of known exposed bedrock removed using the dataset produced by Arosio *et al.* (2023). Both grids were then reclassified on the 1- 5 suitability scale, with the values shown in Table 4.8 below. Minor gaps in the grids, resulting from incomplete survey coverage, were classified as “Marginally Suitable”.

Table 4.8: Sediment Thickness Suitability Score

Sediment Thickness (m)		
Thickness (m)	Value	Suitability
> 4	1	Highly Suitable
3 - 4	2	Suitable
2 - 3	3	Marginally Suitable
1 - 2	4	Unsuitable
0 - 1	5	Highly Unsuitable

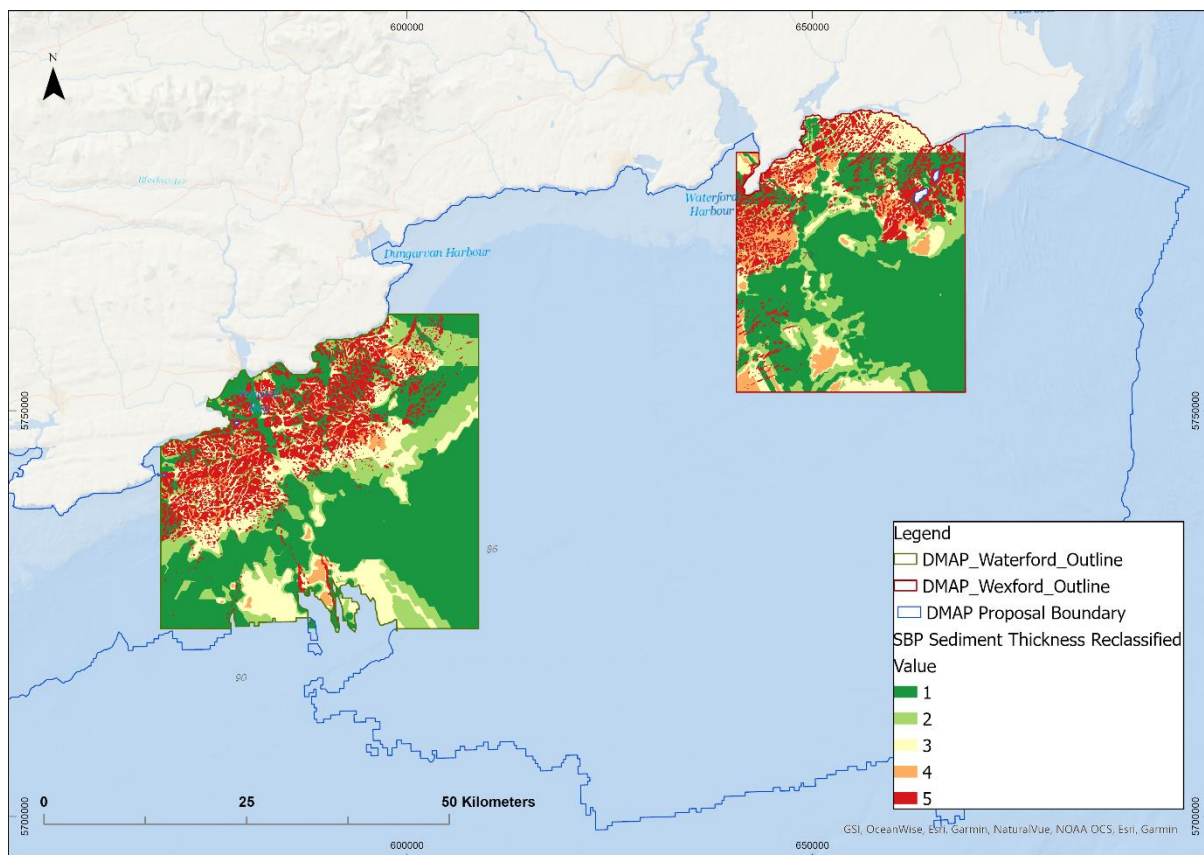


Figure 4.23: Reclassified Sediment Thickness Map - Suitability Scores

Executing a LCPA on the reclassified sediment thickness maps for produced four routes for DMAP_Waterford and three routes for DMAP_Wexford (see Figure 4.24 below).

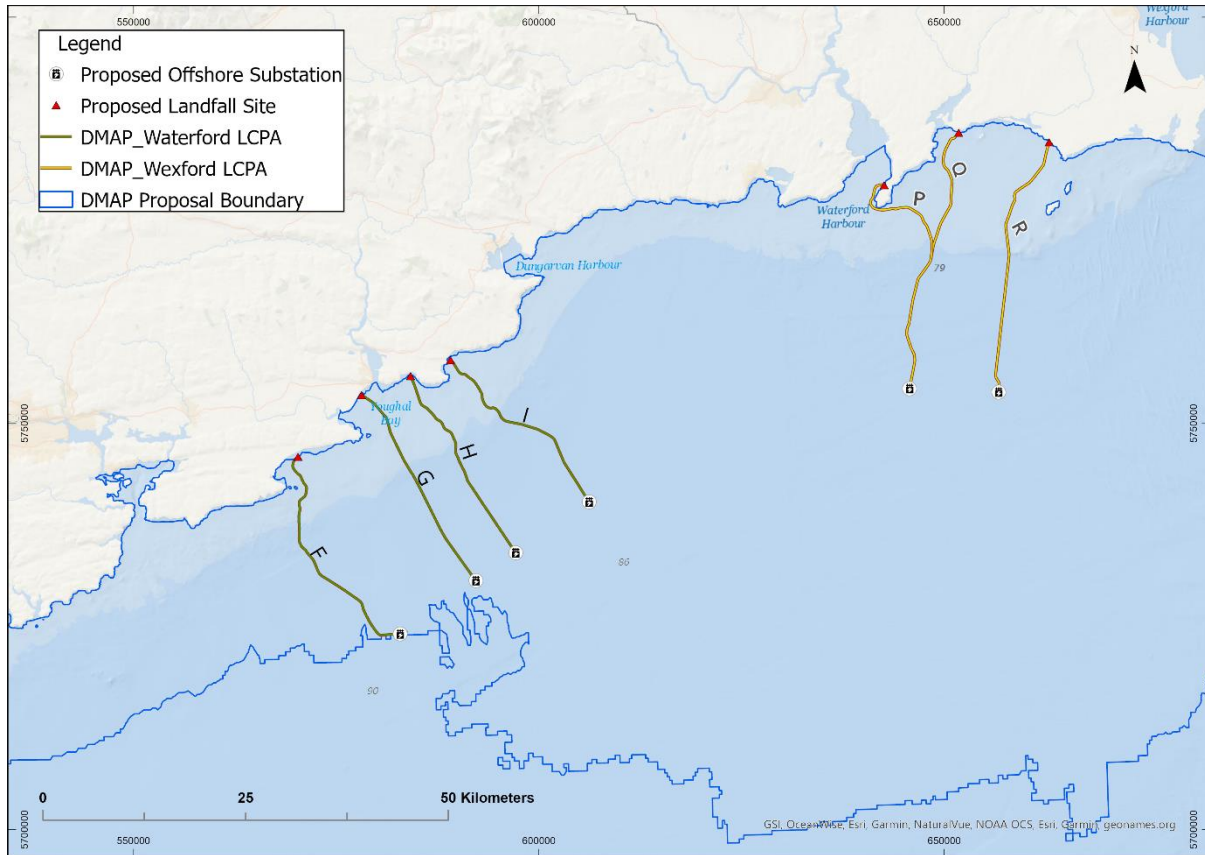


Figure 4.24: LCPA Routes for DMAP_Waterford and DMAP_Wexford

Analysis of the results reveals that for DMAP_Waterford, Route G has the most optimal burial conditions, having both the lowest total cost and the lowest cost-per-km. The route avoids known exposures of bedrock by utilising a well-defined paleochannel which trends in a north-northwest to south-southeast direction from Youghal Bay, Co. Waterford. This channel contains accumulations of sediment of up to ca.20 m thick when identified within the SBP data (Figure 4.25). Grab samples from the INFOMAR dataset taken from within this paleochannel reveal the surficial sediment consists of “Sand” to “sandy gravel” (INFOMAR, 2023d). Route H is also a highly suitable route and is the shortest route overall for this area, however it does cross areas of mapped bedrock in places.

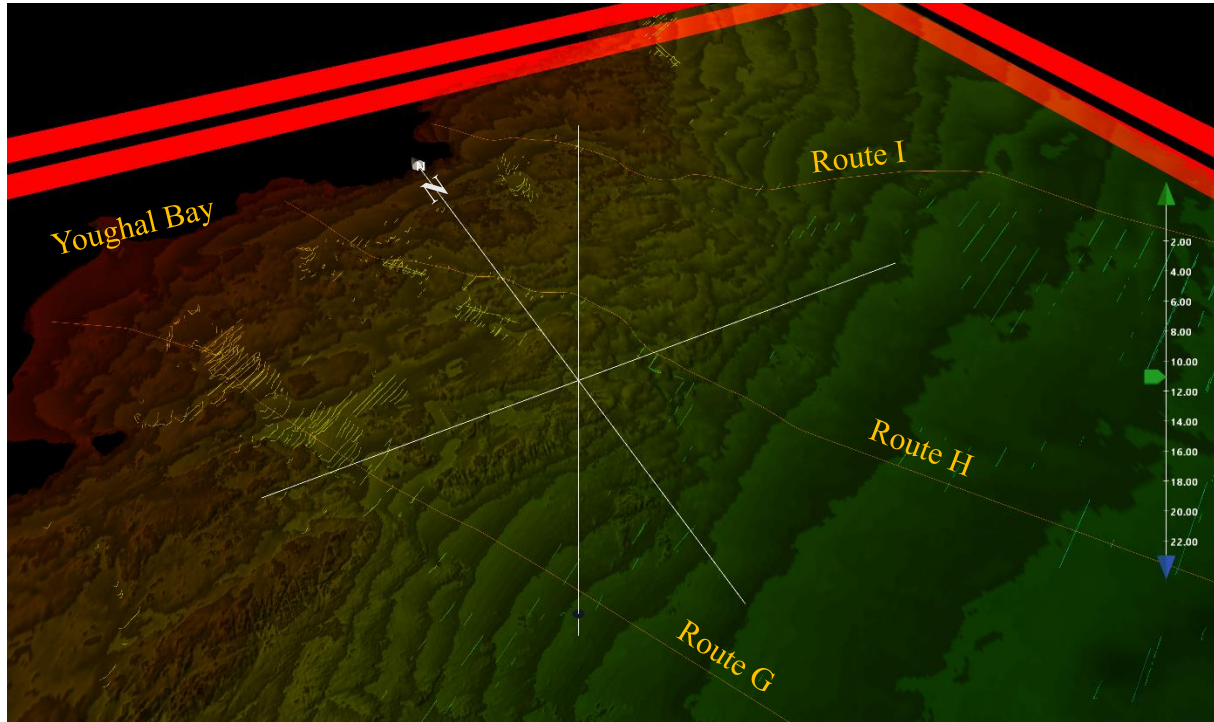


Figure 4.25: 3D view of Digitised Seismic Reflectors, Bathymetry and LCPA Routes

For DMAP_Wexford, Route P is the shortest route with the lowest cost overall. However, the nearshore areas of the route have abundant exposed bedrock, giving the route a higher cost-per-km value when compared to other routes. Route Q is more optimal in this regard, which has the lowest cost-per-km value despite being the longest route for this area. This route is located along a paleochannel which extends southwards from Bannow Bay, Co. Wexford. The SBP data reveals sediment thicknesses of up to ca.14 m along the route with INFOMAR sediment samples comprised of “sand”, “gravelly sand” or “sandy gravel”.

Table 4.9: LCPA Results for DMAP_Waterford and DMAP_Wexford

DMAP_Waterford				DMAP_Wexford			
Route #	Length (km)	Total Route Cost (km)	Cost per km	Route #	Length (km)	Total Route Cost (km)	Cost per km
F	29.83	40.90	1.37	P	32.86	38.62	1.18
G	27.22	31.60	1.16	Q	34.05	38.75	1.14
H	25.99	32.70	1.26	R	33.15	40.78	1.23
I	26.15	34.83	1.33				

The routes shown in Figure 4.24 were optimised solely on the sediment thickness and when compared with the suitability surfaces from the three scenarios some errors are evident. For instance, many of the routes produced by the LCPA of the sediment thickness map for

DMAP_Waterford cross several shipwreck buffer zones. Notably, Route G lies within the buffer zone of the planned route of the Celtic Interconnector, a HVDC cable currently under development that will connect the electricity grids of Ireland and France (EirGrid, 2020). Similarly, routes produced for DMAP_Wexford also intersect and traverse protected sites and exclusion zones. Therefore, the sediment map cannot be used as a stand-alone routing surface. To address this, the protected sites and exclusion zones layer was combined with the sediment thickness map and the LCPA conducted again on the new surface.

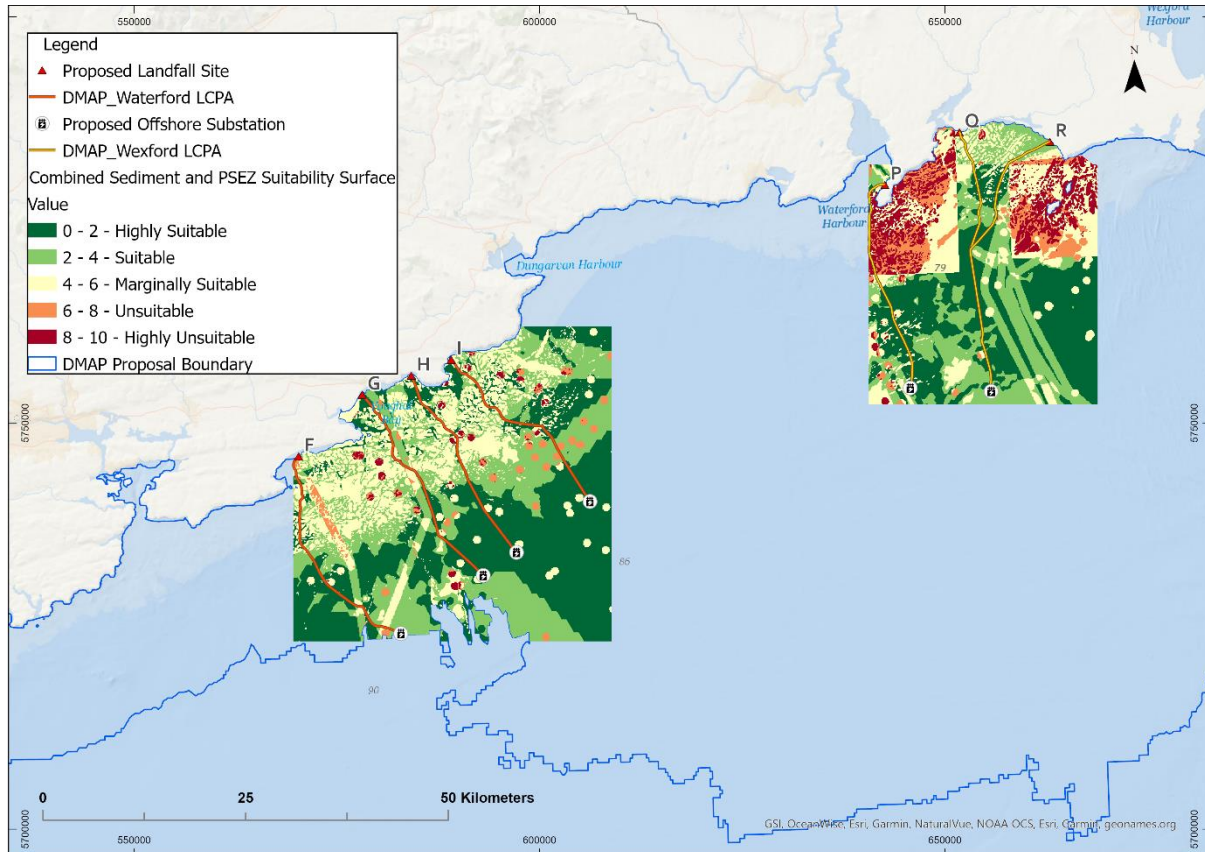


Figure 4.26: Results of LCPA on combined Sediment Thickness and Protected sites and Exclusion zones surface

When the protected sites and exclusion zones are incorporated, Routes I and H prove to be the most preferable for DMAP_Waterford, with a cost-per-km value of 1.18 each, when normalised on the same 1 - 5 suitability scale as the previous surfaces and routes. Routes Q and R have the lowest cost-per-km for DMAP_Wexford, scoring 1.14 and 1.20 respectively.

Table 4.10: LCPA Results for DMAP_Waterford and DMAP_Wexford on combined Sediment Thickness and Protected sites and Exclusion zones surface

DMAP_Waterford PSEZ				DMAP_Wexford PSEZ			
Route #	Length (km)	Total Route Cost (km)	Cost per km	Route #	Length (km)	Total Route Cost (km)	Cost per km
F	28.87	40.18	1.39	P	27.49	59.12	2.15
G	28.23	34.87	1.24	Q	33.07	37.61	1.14
H	26.16	30.80	1.18	R	35.62	42.84	1.20
I	26.32	30.92	1.18				

Based on the results of the SBP data and subsequent LCPA, Routes Q, H and I are the most optimal routes for SECs within the South Coast DMAP area. These routes, with the optimal offshore substation location and landfall site for each, are shown below in Figure 4.27.

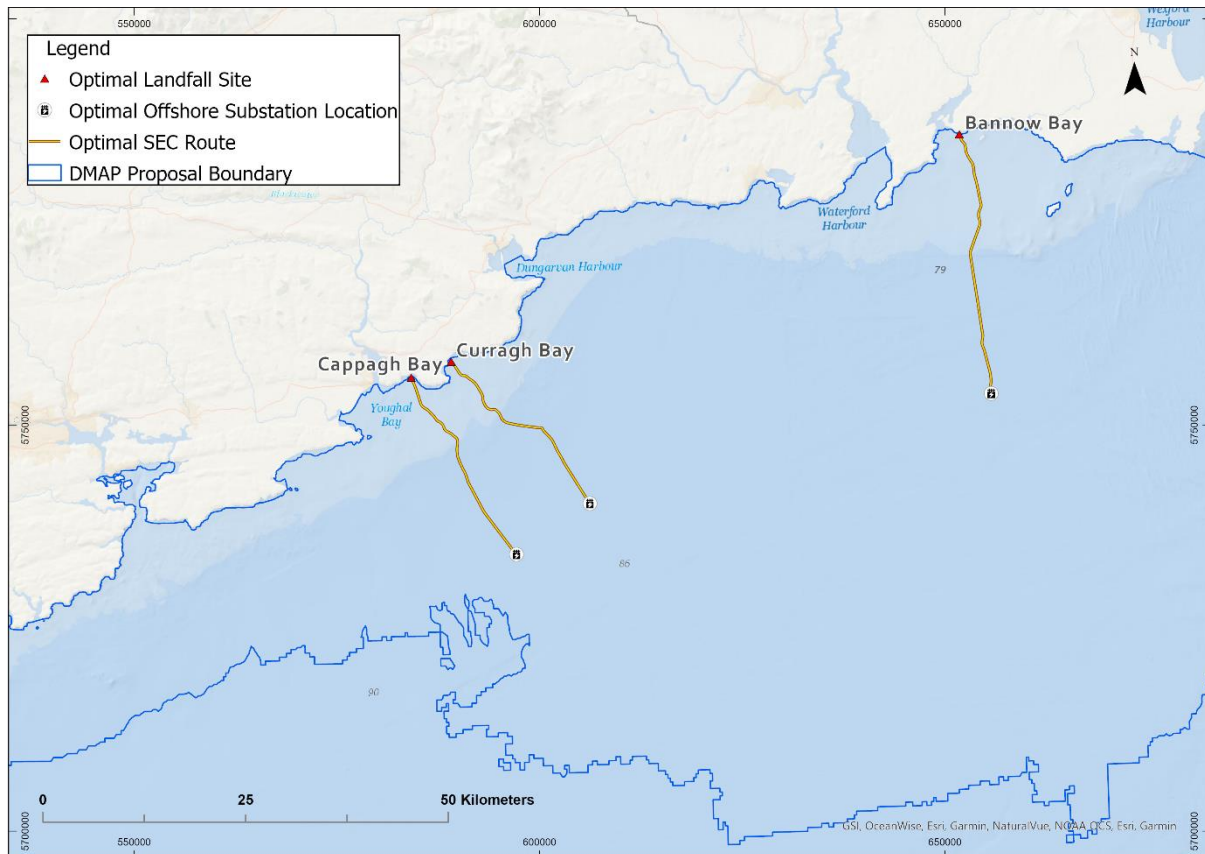


Figure 4.27: Optimal SEC Routes within the South Coast DMAP

5. Discussion

The following chapter delves into the findings of the multi-criteria decision-making analysis, site suitability analysis, route selection, and sub-bottom profile data processing. It provides a comprehensive comparison of these results with existing literature with the goal of answering the main research questions posed by this thesis, detailed in Section 2.8. Additionally, this chapter addresses the limitations of the study and highlights potential areas for further research.

5.1. Submarine Cable Route Feasibility: A Multi-Criteria Decision-Making Approach and its Implications for Offshore Energy Site Selection

The first research question (RQ1) addressed in this thesis focused on how a Multi-Criteria Decision-Making Analysis (MCDA) can identify and prioritise the key criteria influencing the feasibility of a submarine cable route and what the implications are for site selection in the offshore renewable energy (ORE) industry. Following the review of the relevant literature and industrial best practices related to optimal submarine export cable (SEC) routing conditions, six key criteria layers were identified. These were Bathymetry (Figure 3.3), Slope (Figure 3.4), Substrate (Figure 3.5), Distance to Grid (Figure 3.8), Vessel Density (Figure 3.9), and Protected Sites and Exclusion Zones. The latter category encompasses several sub-criteria: Existing Cables and Pipelines (Figure 3.10), Natura 2000 Sites (Figure 3.11), Aquaculture Sites (Figure 3.12), Offshore Dump Sites (Figure 3.13), Shipwrecks (Figure 3.14) and Military Exclusion Zones (Figure 3.15). In studies with a similar scope (Table 3.1), all but one of the aforementioned criteria are included to some extent. Offshore dump sites are not considered in any of these studies, and none of the reviewed research combines all these criteria. This study, therefore, presents a novel approach by incorporating new criteria and integrating all relevant factors into the MCDA, offering a comprehensive representation of site suitability for SECs.

The finalised criteria layers were selected to best address the specific physical and economic conditions of South and West Coast of Ireland. Other studies with a similar scope (e.g. Huang *et al.*, 2018; Wang *et al.*, 2019; Diaz and Guedes Soares, 2022; Makrakis *et al.*, 2023) consider geological hazards, such as submarine faults and volcanoes, to be of high importance, however such hazards are not present in the South and West Coast study area. Instead, the importance of each criterion was weighted based on the anticipated preferences of planners or developers of offshore wind farms (OWFs), with three scenarios proposed. The three scenarios were

designed to investigate the applicability of the Analytical Hierarchical Process (AHP) as an appropriate MCDA technique for site selection for offshore wind energy infrastructure.

The Economic Scenario (Table 4.1) prioritises cost reduction, while the Environmental Scenario (Table 4.2) focuses on reducing environmental impacts. These two considerations, often with conflicting spatial elements, are commonly cited in previous studies (Vasileiou *et al.*, 2017; Effat *et al.*, 2022; Butschek *et al.*, 2023), though differing approaches exist in the literature. Effat *et al.* (2022) used AHP to derive weights for economic, environmental and social scenarios to create suitability surfaces aimed at designing a new road, however each scenario considered unique criteria. In contrast, this study includes all key criteria in each scenario, differing only in weight, which is more similar to the approach by Makrakis *et al.* (2023).

This study, along with others (e.g. Vasileiou *et al.*, 2017; Butschek *et al.*, 2023; Taoufik and Fekri, 2023), underscores the suitability of AHP as an MCDA technique for site selection in ORE projects. The weighting of individual criteria offers a standardised approach that helps planners and developers maintain transparency and accountability in their decision-making. By evaluating all influencing factors early in the process, significant savings can be achieved by prioritising criteria that have the greatest impact on costs, allowing infrastructure to be sited in optimal locations. Likewise, environmental and social concerns can be integrated into the decision-making process, enabling the consideration of diverse stakeholder input during site selection.

In the Irish context, this technique could be employed by the Maritime Area Regulatory Authority when issuing Maritime Area Consents for ORE projects. Beyond Ireland, other countries or regions with nascent ORE industries could utilise AHP when allocating sites for development, adapting the criteria and weights outlined in this thesis to best align with local conditions. This could aid in identifying potentially suitable areas or to pinpoint regions with insufficient data coverage.

5.2. Optimal Seabed Regions for Submarine Cables: Economic vs. Environmental Considerations

The second research question (RQ2) posed by this thesis was concerned with the spatial distributions of the regions on the seabed within the study area deemed most suitable for submarine cables from RQ1, and how the results vary based on economic vs environmental considerations. The resulting map produced by the weights derived from the Economic Scenario highlights two primary areas of suitability (Figure 4.1). The largest of these is within 50 km of the southern coast, extending from Butlerstown, Co. Cork in the west to Carnsore Point in Co. Wexford in the east. This area's high suitability score is largely due to seven existing substations within 20 km of the coast, which could serve as ideal locations for connecting an offshore windfarm to the onshore grid. This area also benefits from relatively shallower waters than the rest of the study area. The second area is located along the coastline of Co. Clare. As with the previously mentioned area, this region's suitability is accounted for by the prioritisation of proximity to existing, suitable grid connection points, which accounts for 42% of the overall weighting in this scenario. The most suitable areas are within 20-30 km of the coast, as water depths increase more rapidly away from the coastline in this region when compared to the southern coast.

Both of the areas mentioned above have already been recognised by developers and government planners as suitable for the development of offshore wind energy (WEI, 2023; DECC, 2023b). The first area, off the southern coast, lies within much of the South Coast Designated Maritime Area Plan (DMAP), while the second area contains the cable route investigation corridors selected by Fuinneamh Sceirde Teoranta, the developers of the Sceirde Rocks OWF (Figure 5.1). This alignment confirms that the weighted values determined for the Economic Scenario accurately reflect the real-world concerns and priorities of OWF planners and developers.

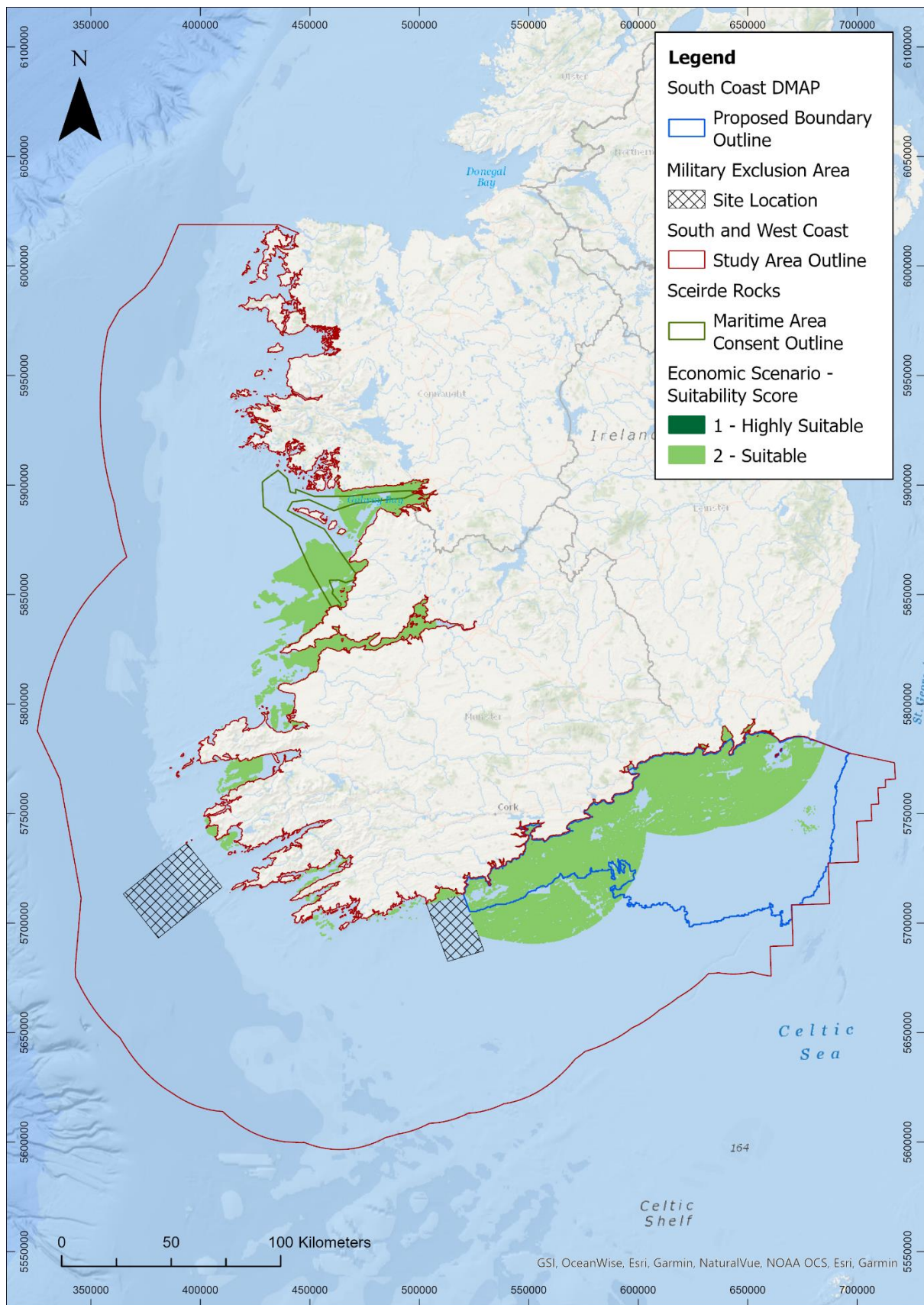


Figure 5.1: Economic Scenario - Most Suitable Regions for SECs

The Economic Scenario identifies the southwestern and northwestern regions of the study area as the least suitable, primarily due to the distance – over 100 km – from existing coastal substations, which exceeds the feasible limit for 220 kV HVAC cable systems (BVG Associates, 2019). Additionally, these areas lack sufficient substrate data, due to incomplete seabed mapping coverage by INFOMAR. The mapped regions reveal considerable exposures of bedrock in many nearshore areas in the southwest and northwest, further contributing to their unsuitability. However, the suitability analysis could be utilised in these areas to identify sites where developing new coastal substations would be most beneficial, should these areas prove suitable for OWFs.

The weights applied in the Environmental Scenario result in a large area of suitability for SEC routes within the South and West Coast (Figure 4.2). This outcome is expected, as avoiding environmentally or culturally protected sites is given the highest priority in this scenario with a 42% weighting. These sites comprise 16% of the total area, and with just 3% of the total area composed of sites which are deemed “Highly Unsuitable” for SECs. It should be noted that this score of unsuitability within one layer becomes diluted when combined with every other layer during the weighted overlay process. As such, offshore dump sites and the buffer zones around shipwrecks, which are deemed the most unsuitable sites in this scenario, become either “Marginally Suitable” or “Unsuitable” in the final map. This will not negatively affect the LCPA routing process, since the cells surrounding these sites will remain preferable, however if the suitability surfaces are to be used for other site selection purposes, the most unsuitable regions could be removed from the surface altogether, as was the case for the military exclusion zone in this project.

The Equal Weighting scenario illustrates the advantages of implementing an MCDA technique like AHP. The equal weighting process generates many areas of suitability similar to those in the Economic Scenario, though these areas are less clearly defined and the meaning behind them can be attributed to multiple factors. The substrate appears to be the most significant, with areas of mapped sandy sediments within 10 km of coastal substations revealing “Highly Suitable” zones around the coast of Clare and the Cork-Wexford coast. The remaining area is classified as either “Suitable” or “Marginally Suitable”, with minor “Unsuitable” regions corresponding to outcropping bedrock, or shipwrecks, off the southwestern coast. While equal weighting of each criterion may have some uses, in practical scenarios, one criterion typically takes precedence over others, and considering all factors equally can lead to undesirable results.

5.3. Least Cost Path Cable Routes: Informing Offshore Windfarm Site Selection

The third research question (RQ3) investigated by this study was: How can Geographic Information Systems (GIS)-based tools for route selection inform the selection of sites for cable routes, offshore substations, and cable landfall points? Furthermore, what practical implications do these tools hold for improving the efficiency and effectiveness of offshore wind farm development projects?

The two case studies discussed – the Sceirde Rocks OWF and the South Coast DMAP (Figure 3.22) – demonstrate the effectiveness of using a LCPA for SEC route selection and how this approach can inform further site selection for an OWF. SEC routes from OWFs are typically designed by a qualified engineer on a case-by-case basis, with the starting point (the offshore substation) and the ending point (the landfall site) predetermined based on the layout of the OWF (Diaz and Guedes Soares, 2020). Such is the case for the Sceirde Rocks OWF, the results of which were detailed in Section 4.3.1. When combined with an LCPA, this approach efficiently produced SEC routes across three scenarios.

The results indicate that, based on all the currently available information, viable routes can be designed for each of the three landfall sites to the offshore substation (Figure 4.12). In practice, a determination on the most optimal route will therefore depend largely on the onshore portion of the cable route, which is outside of the scope of this study. However, based on the results of the LCPA, Route A from the Economic Scenario would appear to be the most optimal SEC route for the Sceirde Rocks windfarm. Table 5.1 below shows the potential additional costs associated with implementing this route, using the mean cost of €3.3 M/km for SEC cables and cable installation derived from the European Union Agency for the Cooperation of Energy Regulators (ACER, 2023).

Table 5.1: Costs of Optimised SEC Route from Sceirde Rocks Offshore Windfarm

Sceirde Rocks Optimised Route						
Route #	Shortest Possible Route length (km)	Cost (M€)	Optimised Route Length (km)	Cost (M€)	Additional Route Length (km)	Additional Cost (M€)
A	61.87	204.17	62.86	207.43	0.99	3.26

The additional 0.99 km of the offshore portion of the export cable route derived from the LCPA could total €3.26M for the Sceirde Rocks project. However, laying a cable along the shortest possible route would also incur additional costs. For example, the optimised route avoids most known exposed bedrock, which is associated with higher costs for cable protection measures when compared to burial within the seabed sediment (BERR, 2008; BVG Associates, 2019).

The case study for the South Coast DMAP poses a different situation, as the locations of the offshore substations and landfall sites have not yet been selected by developers or planners. However, a LCPA can still be applied to identify optimal routes, which in turn can help determine the best locations for these sites. For this study, twenty landfall sites were chosen along the southern coastline by the author, with the goal of avoiding sensitive sea-cliff habitats and providing adequate coverage of the northern boundary of the South Coast DMAP. Offshore substation site selection generally faces fewer constraints than onshore, and by providing a series of potential locations, a LCPA can iteratively determine routes from multiple locations, ultimately identifying the most optimal offshore site.

Offshore substation locations were placed at the 12 nm limit (Figure 3.24), chosen to reduce the visual impact of offshore infrastructure on coastal communities. Given the irregular morphology of the coastline, this visual impact will vary depending on the coastal location. However, siting substations at this limit appears prudent given that the visibility of offshore infrastructure is a common concern of both the public (Ladenburg, 2009) and industry professionals (Butschek *et al.*, 2023). This approach was chosen given the size of the South Coast DMAP. Should a defined site boundary for an OWF be proposed, planners or developers could design a network or grid of potential offshore substations within that boundary, which could then be used to determine the optimal substation site based on a LCPA. Subsequently, the network of intra-array cables connecting the turbines could be designed around this optimised substation location, further enhancing the efficiency of the electricity transmission system within the OWF.

The results of the LCPA for the South Coast DMAP reveal that Routes E-J have the lowest total cost for all scenarios, with landfall sites extending from Ballycotton, Co. Cork in the west to Ballycureen North, Co. Waterford in the east (Figure 4.17). This region defines the DMAP_Waterford area, one of two areas chosen for further sub-bottom profile analysis. These routes benefit from their proximity to several, suitable grid connection points located around Cork City (Figure 3.8). They are also among the shortest routes overall, which reveals a

drawback of using the 12 nm limit. The 12 nm limit is measured from a simplified baseline which smooths out the coast (UNCLOS, 1982), so those landfall sites within indented regions of the coast will be further from the 12 nm limit, resulting in longer, higher cost routes. This can be accounted for by the ‘cost-per-km’ value of each route, which normalises the cost of each route, highlighting each routes overall suitability rather than total length.

Analysing the cost-per-km value for each scenario reveals four main areas of suitability for SEC routes (Figure 4.18). One of these, Route H, falls within the DMAP_Waterford area noted above. The most easterly of the four areas, which contains Routes Q and R with respective landfall sites at Bannow Bay and Ballyteige Bay, Co. Wexford, had the lowest cost-per-km value in the Environmental Scenario. Route Q is also among routes with the lowest overall cost (Figure 4.17). This area appears to have adequate coverage of coarse, sandy sediments, with the resulting paths from LCPA avoiding busy marine traffic routes around Waterford Harbour to the west, and Kilmore Quay to the east. The routes are located surrounding two Special Areas of Conservation (SACs), the Hook Head SAC and the Saltee Islands SAC. These areas contain important Annex I/II habitats such as Large Shallow Inlets and Bays, Reefs and Vegetated Sea Cliffs, which support a diverse array of fauna and flora (NPWS, 2013; 2024).

It has been suggested by Carter *et al.* (2014) that the impact of the installation and presence of submarine cables on the marine environment is negligible, especially when compared to continual human processes such as fishing. Carter *et al.* (2014) also suggest that submarine cables could be installed in designated zones which could serve as Marine Protected Areas (MPA). This approach would protect both the submarine cables and the surrounding marine environment from potentially harmful activities. This proposal aligns with the Irish government's goal of increasing the nation's MPA coverage from 2% to up to 30% by 2030 (DHLGH, 2022b). With this in mind, the area surrounding Routes Q and R, from Hook Head to Kilmore Quay, Co. Wexford, termed DMAP_Wexford (Figure 4.18), was further analysed using sub-bottom profile data.

5.4. Optimising Submarine Cable Burial: Sub-Bottom Profile Analysis

The fourth research question addressed by this study was: How can the integration of sub-bottom profile (SBP) data further optimise cable routes and cable protection strategies in the South Coast DMAP, and what are the implications for cost and risk management in OWF development?

The results of the MCDA and LCPA indicate that the DMAP_Waterford and DMAP_Wexford regions contain some of the most optimal SEC routes within the South Coast DMAP, based on various criteria. However, the data layers used to determine the suitability of these routes are essentially two-dimensional, concerning the surface of the seabed only. Analysis of sub-bottom profile data, provided by INFOMAR (2022), adds three-dimensional information by revealing the thicknesses of sedimentary units beneath the seabed. Given that the Irish Government has identified burial as the preferred method of cable protection for the South Coast DMAP (DECC, 2024), it is essential to understand the vertical extent of seabed sediment when planning SEC routes.

Currently, developers of OWFs often rely on publicly available data for initial site selection and only later invest in acquiring geophysical data, a process that can take 1-2 years and cost upwards of €1 million over the course of surveying an entire windfarm site (BVG Associates, 2019). Developers might discover, after considerable investment, that certain areas are unsuitable, or that more expensive and time-consuming cable protection strategies are necessary due to inadequate sediment thickness. By utilising the publicly available “pinger” data, which are typically overlooked for this work, developers can gain critical insights into potential constraints on cable placement early in the process, potentially reducing the viable area for cables by a significant percentage. This method offers a cost-effective way to make informed decisions before committing to expensive geophysical surveys.

The use of this dataset is especially applicable to the South Coast DMAP, where widespread, outcropping bedrock can be observed in the nearshore environments. This is visible within the SBP dataset and corresponds with the bedrock layer developed by Arosio *et al.* (2023) (Figure 3.7). Additional cross-validation of the interpolated sediment thickness grids with the existing INFOMAR bathymetry grid (INFOMAR, 2023a) reveals many trends and features are identifiable across both datasets, adding a degree of confidence in the results of the SBP processing. For example, the DMAP_Waterford grid (Figure 4.22) shows a thinner band of

sediment through the centre of the area which corresponds to a zone of known bedrock at, or within 1 m, of the surface. A paleochannel extending from Youghal Bay is also seen which shows the same north-northwest to south-southeast trend in both the bathymetry and the interpolated surface. In the DMAP_Wexford grid (Figure 4.22), a curved shaped deposit of sediment 6-10 m thick is visible in the centre of the region. This “lobe” has been discussed in previous work by Murphy *et al.* (2016) where it was identified through a series of “sparker” sub-bottom profile lines - which achieves higher resolution and deeper penetration depths than the “pinger” dataset used in this study. Murphy *et al.* (2016) describe the unit as a curved lens of sediment comprised of a mix of sand and silty sand, with sediment classifications derived from results of previous vibrocore sampling by Dorschel *et al.* (2012).

The LCPA conducted on the sediment map highlights the need for a holistic approach to planning an SEC route, since many of the routes were deemed unfeasible due to existing protected sites and exclusion zones. By incorporating these layers, a more refined LCPA was completed which re-routed some of the paths, producing newly optimised SEC routes for DMAP_Waterford and DMAP_Wexford (Figure 4.26). This reduced the suitability of Route G in DMAP_Waterford, which clearly is an optimal site for a cable route, evidenced by the fact that the Celtic Interconnector has been planned there (EirGrid, 2020).

Routes H and I are the optimal routes for an SEC from an offshore windfarm in this region, spanning 26.16 km and 26.32 km in length respectively and with landfall sites at Cappagh Bay and Curragh Bay, Co. Waterford. Route Q is the most suitable SEC route for DMAP_Wexford, totalling 33.07 km and ending at Ballyteige Bay, Co. Wexford. Route R is also a viable route, its suitability underscored by the presence of three telecommunications cables routed nearby, with landfall sites at Kilmore Quay, Co. Wexford, as per the KIS-ORCA (2023) database.

Table 5.2 below shows the associated costs related to the three most optimal SEC routes within the South Coast DMAP. The optimised Route H produces the lowest additional length at 0.84 km, contributing an extra €2.78M in costs for the cable and installation based on ACER (2023) figures.

Table 5.2: Costs of Optimised SEC Routes within South Coast DMAP

South Coast DMAP Optimised Routes						
Route #	Shortest Possible Route length (km)	Cost (M€)	Optimised Route Length (km)	Cost (M€)	Additional Route Length (km)	Additional Cost (M€)
H	25.32	83.56	26.16	86.34	0.84	2.78
I	24.20	79.86	26.32	86.84	2.11	6.98
Q	31.78	104.88	33.07	109.14	1.29	4.27

As with the Sceirde Rocks example, optimising the routes in this fashion will increase the initial cost due to increased cable material. However, simply laying a cable along the shortest possible route between the offshore substation and landfall site may incur additional cable protection measure costs or place the cable in a location where the risk of cable failure may be higher. Given the extremely high costs of SEC repair, reported to be up to €32M per cable (Unsworth *et al.*, 2023), minimising the risk of damage to the cable could result in significant long-term savings. Therefore, a thorough cost-benefit analysis is essential in planning cable routes to ensure that the selected cable protection strategy is both economically viable and effectively reduces risk to the SEC.

5.5. Limitations

The limitations of using AHP for ORE site selection have been previously highlighted by several authors. For instance, Butschek *et al.* (2021) recommend arriving at a group consensus when deciding on criteria importance, and Vasileiou *et al.* (2017) suggesting applying alternative MCDA techniques to compare with AHP during the site selection process. In response to this limitation, the Equal Weighting Scenario was designed to treat all the criteria in an equivalent manner, an approach also implemented by Makrakis *et al.* (2023) and Effat *et al.* (2023). While this approach may be suitable in certain instances, it is generally considered sub-optimal for site suitability analyses. In such analyses, some criteria are inherently more important than others, and by equalising their weight, much of the detail necessary for making informed decisions is lost. Ultimately, expert opinion is crucial in site suitability analysis to appropriately prioritise the project's goals and ensure the most important criteria are emphasised.

Similarly, the rasterization and reclassification of each layer requires value judgements on the suitability of differing elements within the dataset. For those layers containing individual sub-criteria, such as the Protected Sites and Exclusion Zones layer (Figure 3.21), individual decision makers may assign differing degrees of unsuitability to each criterion depending on their own experience or outlook. Decision makers, scoring each criterion using AHP will differ in the same way. Despite this, it is the opinion of the author that all suitability scores assigned during the data processing can be justified based on the literature, and the development of three weighting scenarios aims to account for the introduction of bias within AHP.

The designation of the relative importance of one criterion over another is inherently subjective, influenced by the biases of the decision maker. The benefit of AHP lies in the transparency of the weighting process and the ability to check the consistency of the values assigned within the pairwise comparison matrix (Saaty, 1980). These scores, as well as the calculations used to determine the criteria weights, are easier to convey when compared with other MCDA techniques, such as those utilising fuzzy logic (e.g. Jiang *et al.*, 2019; Taoufik and Fekri, 2023). This clarity allows for colleagues to clearly understand how the weights are derived and provide input for improvement based on their own judgements. This process fosters transparency and accountability in the planning process, ultimately supporting the long-term viability of projects. Thus, AHP provides a valuable framework for site selection for offshore renewable energy, integrating diverse criteria in a manner tailored to reflect the

priorities of the decision maker. Although the suitability surfaces produced from each weighting scenario differ, the results of the LCPA often highlight the same areas as being the most suitable, with differences in the actual routing dependent on each surface.

The methodology suggested in this study is aimed at providing developers and planners of offshore wind farms with a simple workflow that can be implemented to identify suitable areas for SECs and design potential SEC routes with optimal offshore substation locations. It should be noted the suitability surfaces are at a 100 m resolution, which would only be suitable for designing routes in the feasibility stage of the development process. A more detailed seabed mapping programme would be required along the routes deemed most suitable by the LCPA to meet the standards set by the International Hydrographic Organization (IHO, 2020).

The SBP data utilised within this study provides crucial information on the seabed sediment within two key areas of the South Coast DMAP. It should be noted, however, that the seven INFOMAR surveys that collected this data were completed between the years of 2007 and 2016 (INFOMAR, 2022). This raises the potential issue of outdated information, particularly in morphodynamic regions such as DMAP_Wexford (Figure 4.19), where mobile sediments may have altered the sediment thickness distribution since the SBP survey was conducted. Similarly, the bathymetric (Figure 3.3) and substrate layers (Figure 3.5) represent compilations of multiple INFOMAR surveys dating back to 2006 (Guinan *et al.*, 2020), and minor local variations in present water depths or sediment type distribution may be expected due to sediment mobility.

5.6. Recommendations for Further Study

This thesis outlines the most suitable sites for submarine export cables around the South and West Coast of Ireland based on the results of one Multi-Criteria Decision-Making Analysis (MCDA), the Analytical Hierarchical Process (AHP). Further site suitability exercises could be conducted using other MCDA techniques to compare with the results of AHP. Stakeholder workshops or questionnaires could also be designed to incorporate input from a wide range of stakeholders into the analysis. This could ensure that all viewpoints are considered, thereby improving the social acceptance of the final siting decisions for SECs and related infrastructure.

Given its size, not all suitable areas within the South Coast DMAP were examined in the detail discussed in Section 4.4 of this study. Future studies could consist of further sub-bottom profile analysis to investigate these other areas of suitability, which were highlighted by the Least Cost Path Analysis. In the west surrounding Cork Harbour, Routes A, B, and C have some of the lowest cost-per-km values within the Economic and Equal Weighting Scenarios. This is primarily accounted for by the four substations located surrounding Cork City. The substations at Long Point and Aghada, are situated right on the harbour, just metres from the waterline. These would be convenient grid connection points for an SEC, requiring minimal onshore routing.

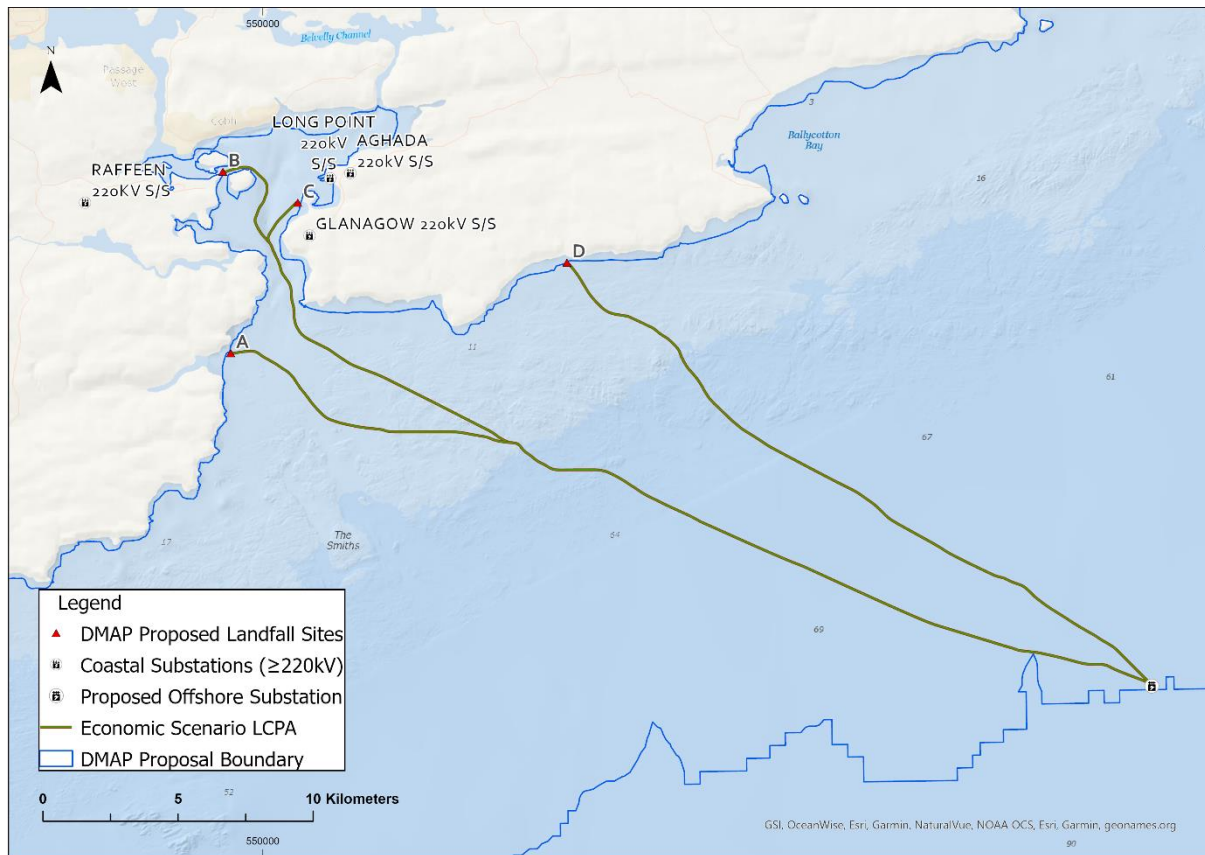


Figure 5.2: Optimal SEC Routes with Landfall sites surrounding Cork City

The second area worthy of further analysis is located in County Waterford, east of Dungarvan Harbour, see Figure 5.3 below. Routes K and L, with respective landfall sites at Clonea Bay and Bunmahon Beach, have low cost-per-km values in all three scenarios, shown in Figure 5.3 below. However, only one suitable substation currently exists within 20 km of either landfall site, at Cullenagh, Co. Waterford. This emphasises that further development of onshore grid infrastructure is required to connect OWFs with the grid and using the offshore suitability surfaces to inform site selection for such projects present a further avenue of study. The LCPA could also be implemented for the onshore portion of the export cable route, integrating economic, environmental and social impacts of potential routes along existing road networks.

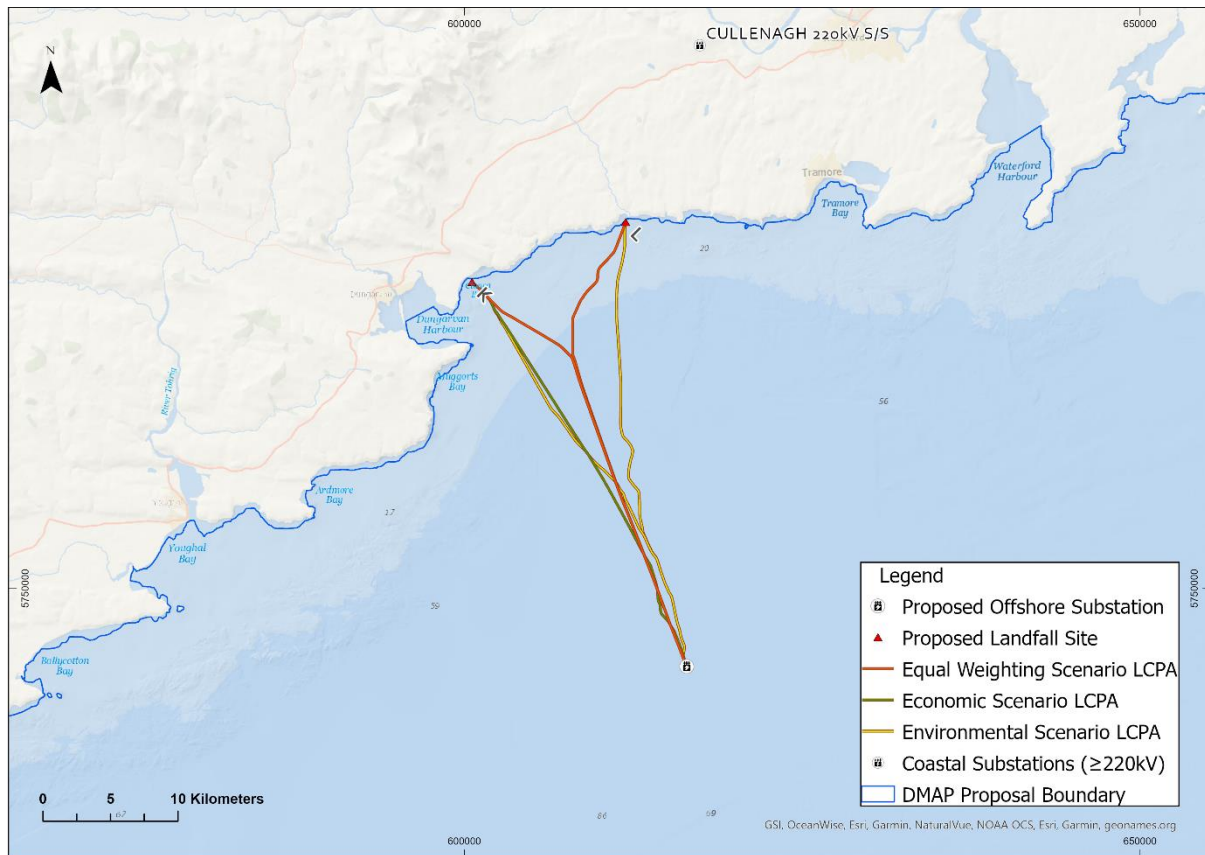


Figure 5.3: Optimal SEC Routes with Landfall sites east of Dungarvan, Co. Waterford

Another research direction for the South Coast DMAP, or other locations around Ireland, could involve exploring the integration of offshore ‘cable protection zones’ and Marine Protected Areas (MPAs), as proposed by Carter *et al.* (2014). The long-term effects of submarine export cables, and any materials used to protect those cables, on the marine environment should be assessed to anticipate any positive or negative impacts. Research focusing on cobble reef restoration shows positive outcomes for many marine species (Casabona *et al.*, 2024), suggesting that cable protection measures designed in alignment with reef restoration could offer a net benefit to the marine environment. Such a study would achieve the dual purpose of promoting development of clean energy resources whilst also protecting, or restoring, sensitive marine habitats.

6. Conclusion

This thesis has demonstrated a comprehensive approach to designing optimal routes for submarine export cables from offshore wind farms. The research identified promising areas around the South and West Coast of Ireland, providing valuable insights into the geomorphology of this region and the current distribution of suitable energy infrastructure along the coast. By leveraging high-quality datasets, available openly through numerous sources, this research underscores the wealth of information accessible to stakeholders involved in the development of offshore renewable energy around Ireland.

With the ambitious offshore energy capacity targets set by the Irish Government (DECC, 2023b), Ireland's energy landscape is poised for dramatic changes in the coming decades. The suitability surfaces, optimised cable routes and sediment thickness maps generated in this study, offer valuable tools for planners and developers of offshore renewable energy projects. By focusing on minimising environmental impacts and reducing costs associated with submarine export cable installation and protection measures, this thesis contributes to advancing offshore wind energy initiatives and supporting national and EU energy goals.

In conclusion, this research delivers actionable insights for immediate use and lays the groundwork for future studies in offshore spatial planning. By integrating a Multi-Criteria Decision-Making Analysis, automated route selection tools, and sediment thickness assessments, it effectively addresses the complex factors involved in designing optimal submarine export cable routes. This approach ultimately supports the sustainable development of offshore renewable energy resources in Ireland, helping to secure a long-term, reliable supply of clean energy for the nation.

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