TOBIN

Rooaunalaghta Green Energy Project

Appendix 8-1

Karst Assessment

ROOAUNALAGHTA
Green Energy

BUILT ON KNOWLEDGE

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SUMMARY

TOBIN has undertaken a karst assessment for the Proposed Rooaunalaghta Wind Farm, Glencorrib, Co. Mayo. The assessment has been undertaken due to the identification of karst features within the 2 km study area of the proposed wind farm site and substation.

The purpose of this report is to evaluate the potential risks to karst associated with the construction and operation of the proposed project and to outline mitigation measures and recommendations for consideration at the detailed design and construction stages. Works for the TDR include hardcore at one roundabout along with some demounting of signs or hedge trimming. As no significant works are required for the TDR, this is screened out from further assessment in this report.

The assessment was completed using a staged approach. Firstly, a desk study was undertaken to identify potential karst indicators from published datasets, aerial imagery and topographic information. Secondly, field walkovers were completed to verify desktop observations and identify additional karst features. Thirdly, targeted intrusive ground investigations were undertaken to characterise subsurface conditions and confirm bedrock structure. Finally, geophysical surveys were completed in selected infrastructure locations to assess bedrock variability, weathering and the potential presence of voids or dissolution features. The results of all elements were integrated within the karst hazard assessment.

A total of five potential karst features have been identified within 1km of the proposed wind farm site. The assessment findings indicate that the majority of the proposed infrastructure is located within areas of low to medium karst susceptibility, reflecting the presence of shallow limestone bedrock and a regionally important karstified aquifer. Site walkovers, geophysical surveys and intrusive ground investigations identified no evidence of significant subsurface cavities beneath the proposed infrastructure footprints.

While localised areas of higher karst hazard occur within the wider site, these areas have been avoided through the design process, and no turbines, hardstands, access tracks or substation infrastructure are located within mapped karst features or areas assessed as high or very high karst hazard. No identified karst feature occurs within the proposed infrastructure footprint.

Subject to implementation of the proposed embedded mitigation measures and Karst Management Protocol, the residual risk associated with karst is considered low and no significant effects on geological, hydrogeological or karst receptors are predicted.

1. INTRODUCTION

1.1 SITE LOCATION & ENVIRONMENTAL SETTING

The proposed project, known as Rooaunalaghta Green Energy Project, is located in County Mayo with some elements in County Galway. The proposed wind farm site and 110 kV substation includes the construction of 13 no. wind turbines and ancillary works, installation of the 33 kV private grid connection cable along the Grid Connection Route (GCR) with a proposed new loop-in 110 kV substation with associated works (including two steel lattice end masts) to connect to an existing overhead line. It also includes temporary accommodation works (nodes) on the proposed Turbine Delivery Route (TDR). A full description is included in Chapter 2 of the submitted EIAR.

Temporary accommodation works (nodes) associated with the TDR will not require specific karst considerations as works comprise only hedge/vegetation trimming, temporary signage demounting and works to a small area of existing footpath which are not considered significant. The TDR is therefore not considered further in this document.

This assessment relates to the wind farm site. The land use on the site is predominantly agricultural land. There are existing internal access tracks across the proposed wind farm to facilitate the ongoing farming operations. The wind farm site is characterised by gently rolling to locally steep topography.

The study area for this assessment is defined by the methodology (see Section 2), i.e. 250m for karst methodology criteria. A wider study area of 2 km, as per the assessments in Chapter 8 of the EIAR, is used for further context.

1.2 DEFINITION OF KARST

Karst is a landscape with distinctive hydrology and landforms that arise when the underlying rock is soluble. Although karst can develop on evaporate rocks such as gypsum the vast majority of karst landforms are found on carbonate rocks, such as limestones. Karst landscapes may have sinkholes, caves, enclosed depressions, disappearing streams, springs and sinkholes[1].

Karstification is an important process in Irish geology. It involves the enlargement of rock fissures when groundwater dissolves the fissure walls as it flows through them. The process can result in significantly enhanced permeability and groundwater flow rates. It occurs in 'purer' limestones. Pure, clean coarse limestone (90–100% calcium carbonate $CaCO_3$) is prone to dissolution by rainfall. The enlargement (by dissolution) of geological discontinuities (joints, fractures, etc.) leads to the formation of a distinctive karst landscape which includes landforms such as closed depressions (dolines), sinkholes, springs, turloughs (seasonal lakes which occur in winter and early spring when the groundwater table rises above the land surface) and caves.

[1] (https://www.gsi.ie/en-ie/programmes-and-projects/groundwater/activities/understanding-irish-karst/Pages/What-is-karst.aspx)

2. METHODOLOGY

The karst risk assessment methodology is based on the approach adopted for road schemes in Ireland (Madden and O'Hara, 2016, and Rutty and Jennings, 2012); published literature (Waltham et al., 2005); and project expertise of the project team on large infrastructure projects in karstic environments including the M17/M18 motorway project. Experience in the construction of a number of wind farm projects constructed and operational in areas of karstified and dolomitised limestone including three wind farms at Lisheen, Co. Tipperary, Carrickeeny and Manorhamilton, Co. Leitrim, Mount Lucas, Co. Offaly and four other windfarms in Galway/Mayo .

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2.1 DESK STUDY

A desk study was undertaken to collate and review background information of the receiving environment. The following publicly available data sources and datasets were consulted:

- Geological Survey Ireland (GSI) datasets, including the karst feature database, bedrock geology, quaternary geology, and extractive industry data[2];
- Environmental Protection Agency (EPA) datasets on soils, subsoils, and land cover[3];
- National Parks and Wildlife Service (NPWS) data on designated conservation sites[4];
- GeoHive platform for mapping, topographic, and base imagery data[5];
- LiDAR (Light Detection and Ranging) data and other publicly available digital elevation models (DEMs) to support interpretation of topography and geomorphology;[6]
- Aerial imagery from the following sources has been used to identify potential karst features:
    - Bing Aerial Imagery (Jan and Sept 2025);
    - Google Earth Multitemporal Aerial Imagery (2009-2025);
    - Ordnance Survey Ireland Orthophoto (OSi, 1995-2013); and
    - OSI 6-inch and 25-inch historic base mapping.

2 Geological Survey Ireland (GSI). Available at: https://www.gsi.ie/en-ie/data-and-maps/Pages/default.aspx
3 Environmental Protection Agency (EPA) Maps and Data. Available at: https://gis.epa.ie/EPAMaps/
4 National Parks and Wildlife Service (NPWS) Map Viewer. Available at: https://www.npws.ie/maps-and-data
5 GeoHive Public Mapping Platform. Ordnance Survey Ireland. Available at: https://www.geohive.ie/
6 Lidar and Digital Elevation Models from Bluesky, Geological Survey Ireland and Ordnance Survey Ireland via GeoHive. Available at: https://www.geohive.ie/ and GSI's Open Topographic Data Viewer (https://dcenr.maps.arcgis.com/apps/webappviewer/index.html?id=b7c4b0e763964070ad69bf8c1572c9f5)

2.2 SITE WALKOVERS, GEOLOGICAL & KARST FEATURE MAPPING

To aid in the identification and mapping of potential karst features across the proposed wind farm site. Five site walkovers were also conducted in May 2025, November 2025, February 2026, April 2026 and July 2026, to assess the ground conditions at the proposed wind farm site. The survey work was completed by Peter McSherry (BSc, MSc, PGeo) and John Dillon (BSc, MSc, MCIWM, PGeo). John Dillon who has over 20 years' professional experience including 10 years with karst assessment while Peter has 5 years of professional experience. The purpose of the karst walkover was to:

- Examine exposed soils, subsoils and bedrock;
- Verify and record the presence of potential surface karst features identified from the desk study; and
- Identify any karst features not visible from the desk study.

2.3 GROUND INVESTIGATIONS AND GEOPHYSICAL SURVEY

The Site Investigation (SI) methodology is described in Section 8.3, Chapter 8 of the EIAR. The SI results are summarised in Table 8-5, and the investigation locations are shown in Figure 8-9 of the EIAR.

All exploratory locations were surveyed, and their positions and elevations were accurately recorded using standard coordinate and elevation references. Laboratory testing was conducted on samples collected and included geotechnical analysis of soil samples — covering moisture content, Atterberg Limits, particle size distribution, compaction characteristics, and pH, as well as rock testing for Point Load Index and Slake Durability. All testing was carried out in accordance with BS 1377 and relevant rock mechanics standards. The ground investigation was completed in accordance with Eurocode 7 – Geotechnical Design, Part 2 (EN 1997-2) and BS 5930:2015 – Code of Practice for Ground Investigations. Mineral subsoils were logged according to BS: 5930.

All field work was conducted in compliance with best practice standards and relevant guidance, with oversight from qualified geologists and engineers. The site investigation works outlined above locations are shown on Figure 8-9, Chapter 8 Volume II of the EIAR.

Based on the findings of the desk study, a geophysical survey was undertaken by Minerex Geophysics. The geophysics investigation that was undertaken comprised the following survey methods:

- 15 No. Electrical Resistivity Tomography (ERT) and
- 15 No. seismic profiles

3. SITE CHARACTERISATION

3.1 GEOLOGICAL SETTING

The bedrock geology underlying the proposed wind farm site, GCR and substation is shown in Figure 8-7, Chapter 8, Volume II of the EIAR. The proposed wind farm site is underlain by Dinantian limestones comprising bedrock formations detailed in Table 3-1. Bedrock outcrops are present across the proposed wind farm site, particularly concentrated to the north and centre. Regional geological mapping indicates the presence of structural lineaments and mapped faults (>1km from the wind farm); however, no significant fault structures have been confirmed within the proposed wind farm site. Structural controls may have influenced localised dissolution and weathering of the limestone bedrock but do not represent a significant development constraint.

Table 3-1 Bedrock Formations - proposed wind farm site

Formation	Location	RUGS group	Lithology
Oakport Limestone Formation	Dominant lithology throughout the site.	Dinantian Pure Bedded Limestone	Dark crinoidal calcarenites and shales – site investigation information indicates Very strong locally strong thinly bedded grey bioclastic fine and coarse grained limestone.
Old Chapel Limestone Formation	Lithology located towards the south of the site.	Dinantian Pure Bedded Limestone	It comprises bioclastic calcarenites with a relative abundance of macrofauna of brachiopods and corals. Chert nodules occur throughout but are more common in the middle of the formation
Illaunagappul Formation	Lithology located towards the south of the site.	Dinantian Pure Bedded Limestone	The formation consists of dark grey to black, fine-grained calcarenites (packstones with peloids).
Ardnasillagh Formation	Lithology located along the GCR	Dinantian Pure Bedded Limestone	The formation consists of dark cherty limestones and thin shales



Image 3-1 Photo of old quarry facing south. Reservoir fencing evident on right of photo. Bedrock is competent and dips <2deg to the south.

3.2 KARST FEATURES

No karst features are mapped on the GSI karst database[7] within the proposed wind farm site, substation and GCR. A total of five unmapped karst features were identified from the desk study using aerial photography, LiDAR data and site walkovers in the wind farm study area, see Chapter 8, Volume II of the EIAR. These karst features include dolines (enclosed depressions) with a losing stream/drain noted. The distribution of their locations is presented in Figure 3-1 below.

From the site walkovers five features were mapped: four enclosed depressions (dolines) and a section of losing stream. Table 3-2 summarises the mapped karst features on the wind farm site. In general, the enclosed depressions (dolines) were circular in shape, had a bowl-like morphology, and are 0.5 m in depth. A drainage channel located near T10 exhibits intermittent flow losses where sections of the channel bed become dry during low-flow conditions. No point recharge feature was identified during the walkover surveys. The feature is therefore interpreted as a localised losing section of drainage channel associated with permeable limestone-derived deposits. The stream becomes permanent near the southern wind farm site boundary, emerging at the base of some gravels.

7 https://gsi.geodata.gov.ie/portal/apps/webappviewer/

Table 3-2 Karst Feature Summary

ID	x	y	Dimension	Type	Description	Distance to infrastructure
1	523681	749957	6 x 5m	Doline	Shallow oval shaped depression – near T1	60 m
2	523567	750000	25 x 16	Doline	Shallow oval shaped depression - near T1	120 m
3	523162	749256	30 x 20 m	Doline	Shallow oval shaped depression - near T3	700 m
4	530846	750818	30 x 25m	Doline	Shallow oval shaped depression – near GCR/substation	200 m
5	525044	750853	<1m wide Small ephemeral drain	Losing stream	Section of losing stream near T10	120 m

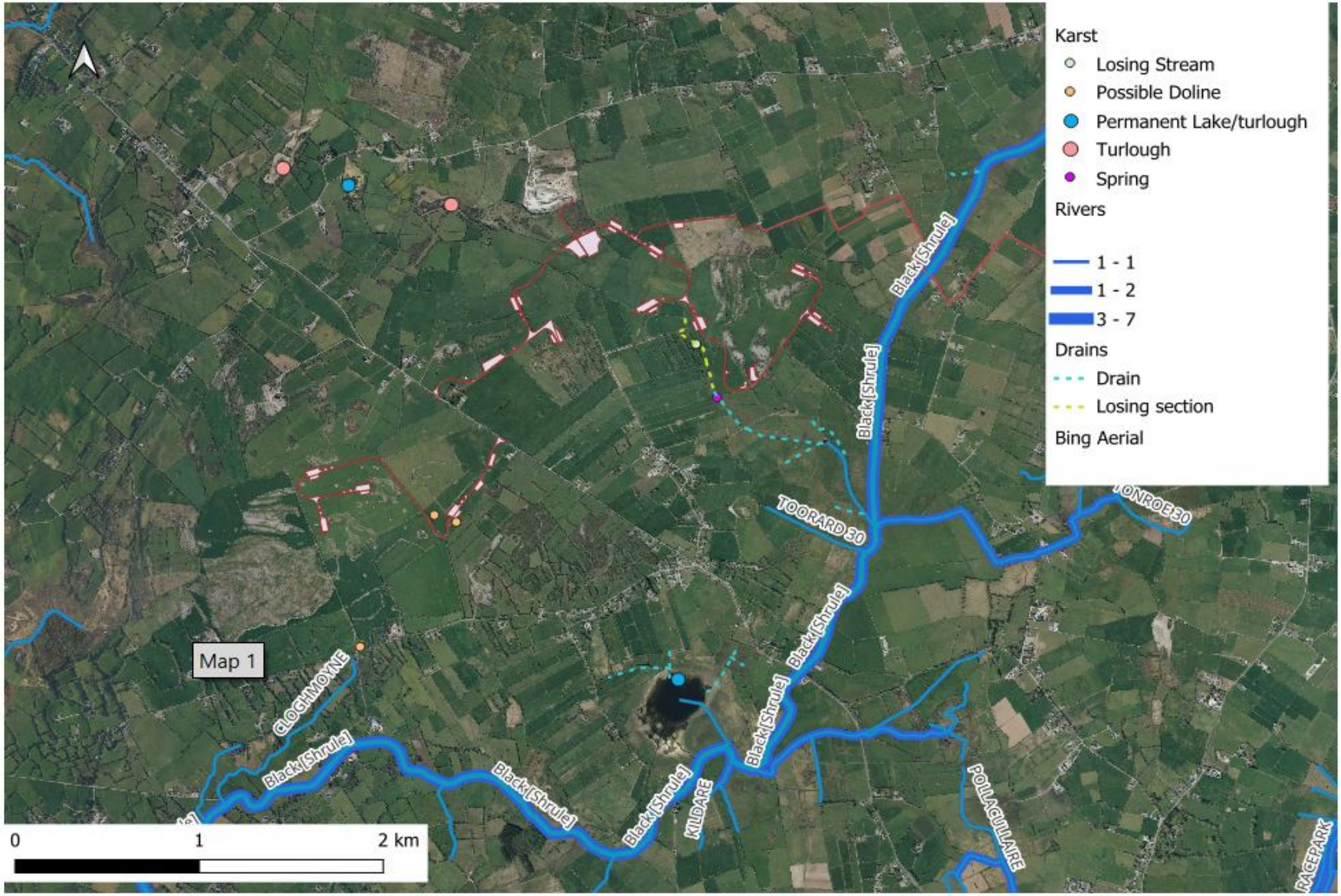


Figure 3-1 Karst Locations

3.3 SUBSURFACE CONDITIONS

The following subsoils and Quaternary sediments are present within the proposed wind farm site boundary (Figure 8-5 and 8-6, Chapter 8, Volume II of the EIAR):

- Karstified Bedrock Outcrop or subcrop (KaRck);
- Bedrock outcrop or subcrop (Rck)
- Silty to gravelly till derived from limestones
- Alluvium (A).

The proposed wind farm site is generally overlain by a thin mantle of topsoil, gravelly silt, sandy silt and limestone-derived gravel, with the nature and thickness of the overburden varying across the proposed wind farm site. The majority of trial pits encountered granular glacial deposits comprising sandy gravel, gravelly silt, cobbles and occasional boulders derived from limestone. Topsoil thickness is typically less than 0.5 m, with shallow granular subsoils commonly extending to depths of between 1 m and 5 m bgl. These deposits are generally firm to dense and provide evidence of glacially derived materials reworked from the underlying limestone bedrock.

Localised peaty and organic soils (0.4 m) were encountered at the proposed 110 kV substation location where thin peaty horizons overlie gravelly silts and sands. Some locations, including T6 and portions of the on-site control building area, contain predominantly silty deposits with frequent cobbles, while other turbine locations such as T3, T5, T8 and T10 are dominated by coarse granular gravels and boulder-rich horizons. The overburden is therefore heterogeneous but is generally characterised by a predominance of granular materials with relatively low compressibility.

Weathered limestone was encountered beneath the overburden, with a gradual transition from glacial deposits into more competent bedrock. Rockhead is generally shallow, typically occurring between approximately 1 m and 5 m bgl where proven. The predominance of granular soils and limestone-derived gravels suggests a relatively low potential for concealed collapse-type karst features within the overburden; however, localised variability in rockhead elevation and the presence of weathered rock zones require management.

No peat material was encountered during the site walkovers or during site investigation works on the wind farm site. A thin layer of peaty topsoils (up to 0.4 m thick), observed at TP-14, at the proposed 110 kV substation. The land at the substation site is flat, drained and in intensive agricultural production. Additional peat probing in July 2026 at the substation building encountered 0.3 m of peaty topsoil. Generally, the soils encountered during the site investigation works were as expected for this region, and predominantly consisted of topsoil overlying glacial tills, overlying bedrock.

The pits were excavated to depths ranging from 0.60 m to 2.90 m below ground level (bgl). Topsoil consisting predominantly of firm brown gravelly silt with frequent cobbles to firm brown silt to soft brown peaty silt (TP-14 & TP-15) was encountered in the trial pits at depths ranging from 0.15 m to 0.50 m depth. The glacial till like soils in general consisted of gravelly silt to sandy gravel to coarse sand and gravel to gravelly sandy silt with occasional to frequent

cobbles and boulders. All trial pits were dry during excavations. Depth to bedrock is approximately 2m on average across the site.

Intact bedrock was encountered in the rotary core boreholes at depths ranging from 1.10 m bgl to 4.90 m bgl. The bedrock is generally described as very strong, locally strong, thinly bedded, grey, slightly bioclastic, fine- and coarse-grained Limestone with subvertical and horizontal white calcitic veinlets.

For detailed descriptions of the ground conditions encountered please refer to the geotechnical logs which are included in Appendix 2-5.

Additionally, the investigations assessed soil composition, bedrock depth, groundwater conditions, and potential subsurface instability. Table 8-5, Chapter 8, Volume II of the EIAR summarises the SI data findings.

Soil samples were collected during the SI works, with samples submitted for geotechnical analysis including moisture content, Atterberg testing, particle size distribution and point load testing. These tests provided essential data on soil properties, ensuring compliance with engineering standards for the proposed wind farm site and proposed 110 kV substation. The laboratory testing results can be located in Appendix 2-5.

Three boreholes were finished as groundwater monitoring wells. BH-01 was completed with a PVC slotted screen from 2.3 m to 6.3 m below ground level. BH-05 was completed with a PVC slotted screen from 3.5 m to 6.4 m below ground level and BH-07 was completed with a similar slotted screen from 7.0 m to 10.2 m below ground level. A disused groundwater abstraction borehole also provided groundwater level data.

Based on the borehole data the subsoils comprise silty or gravelly till derived from limestones. As detailed in Table 8-5 the proposed wind farm site is underlain by weathered limestone bedrock and strong to very strong thinly bedded grey bioclastic fine-grained and coarse-grained LIMESTONE. Weathered zones are typically confined to the top 2-3 m. No record of cavities was encountered during the drilling – see Appendix 2-5.

3.3.1 Geophysics

Geophysics was undertaken at turbines, borrow pit and proposed 110 kV substation locations. The geophysical surveys carried out at the proposed wind farm site consisted of 2D-Resistivity (ERT) and Seismic Refraction (p-wave). There was a strong correlation between both geophysical survey methods, and a combined interpretation has been made using both methods. The data was modelled with 3 layers based on the 2D-Resistivity and seismic velocities. Layer 1 is interpreted as soft or loose soil and the thickness of this layer across the site is up to 2 m. Limited areas of karstified/weathered limestone were found at a number of geophysical survey locations.

Results indicate that most turbine locations are underlain by competent limestone at shallow depths of approximately 1-2 m bgl. Areas of partially karstified or weathered limestone were identified at T2, T6 - T10 and the proposed 110 kV substation.

The geophysical survey and intrusive investigation indicate that the area around BH8 has good potential as a borrow pit. BH8 encountered glacial till, underlain by weathered limestone and then strong to very strong limestone bedrock from about 4 m depth. The geophysical survey confirms a consistent subsurface profile comprising a thin soil layer, weathered limestone and underlying good quality limestone, with no evidence of karstification. Rock quality is generally

high, with strong point-load strengths and good rock quality designation values, suggesting the limestone would be suitable for producing rock fill, engineered fill and crushed aggregate for wind farm construction. No dissolution cavities, voids or significant geophysical anomalies indicative of karstification were identified within the proposed borrow pit area.

4. KARST HAZARD ASSESSMENT

The hazard assessment framework has been adapted from the karst risk assessment methodologies described by Madden and O'Hara (2016), Rutty and Jennings (2012) and Waltham et al. (2005), and modified to reflect the site-specific geological conditions encountered at the proposed wind farm site and 110 kV substation.

The identified karst features inventory provides the basis for the hazard assessment and allows the proximity of infrastructure to identified karst features to be assessed. Table 3-2 summarises the location, dimensions and characteristics of the karst features identified during the assessment These oval/circular features display varying diameters. The morphology suggests that these features are most likely enclosed depressions (dolines), with limited permeability.

The proposed design has avoided the identified karst features (i.e. Dolines and losing stream/drain) and applied a 30 m buffer. The number of identified karst features within 250 m of turbines and the substation has been determined using *ArcGIS Pro*. A 250 m buffer has been used for this analysis as this is considered to provide a localised, yet sufficiently broad, spatial context to capture nearby karst features that may pose indirect or cumulative risks to infrastructure. A high density of karst features within 250 m indicates that the development of karstic features at the location being assessed is more likely. There are two or less karst features within 250 m of the various infrastructure i.e. turbines, construction compounds, borrow pits, substation and LiDAR unit. Details of the karst features are identified below in Table 3-2.

A qualitative Karst Hazard Assessment was undertaken to identify areas where karst features may present a geotechnical risk to the proposed wind farm and 110 kV substation site.

The assessment adopts a risk-based approach that considers both the likelihood of karst occurrence and the potential interaction between karst features and the proposed wind farm and 110 kV substation site .

Particular emphasis has been placed on evidence obtained from site investigations and walkovers, which provide a greater degree of confidence than desk-based mapping alone. As a result, the assessment considers both the regional karst setting and site-specific ground conditions when assigning hazard ratings.

The methodology follows established Irish karst assessment approaches and is based on the principle that karst hazard is influenced by both the geological conditions that favour karst development and the presence of evidence indicating existing karstification. The assessment was completed using information obtained from the desk study, karst feature mapping, site walkovers, ground investigations and geophysical surveys.

Based on information contained in Chapter 8 and 9, Volume II of the EIAR, the original hazard matrix reflects the site-specific karst setting, identified karst features, groundwater vulnerability, infrastructure avoidance measures and receptor sensitivity, rather than using a simple hazard ranking approach. Chapter 8 and 9 of the EIAR identifies:

- Predominantly Extreme (E) and Rock at Surface/Karst (X) groundwater vulnerability.
- Regionally Important Karstified Aquifer (Rkc).

- Four unmapped dolines/enclosed depressions identified from LiDAR/aerials and walkover surveys.
- A losing stream occurs approximately 100 m southwest of T10.
- No surficial karst features are directly located on turbines, hardstand, proposed 110 kV substation or GCR infrastructure.
- No evidence of active swallow holes or direct point recharge features within proposed infrastructure footprints. Where dolines are present these do not appear to be point recharge locations as they appear to represent topographic depressions underlain by low permeability material.

The karst hazard assessment is based on multiplication of four geological factors (A-D – see Table 4-1 below) and two evidence-based factors (E-F):

Hazard Score = (A × B × C × D) × (E × F)

Maximum possible score = **288**.

Karst hazard has been assessed using a matrix scoring methodology that considers both geological conditions favourable to karst development and direct evidence of karstification. The selected factors reflect the principal controls on dissolution feature development including bedrock type, structural influence, overburden characteristics and the presence of nearby karst features – See Table 4-1 below.

Table 4-1 Hazard tables[8]

Factor	Criterion	Score
A. Bedrock Type	Pure limestone	2
	Impure limestone	1
	Non-carbonate rock	0
B. Geological Boundaries/Faults	Within 100 m of fault	2
	>100 m from fault	1
C. Overburden Thickness	0-5 m	3
	5-10 m	2
	>10 m	1
D. Overburden Type	Cohesive till/clay	2
	Granular deposits	1
	Peat	1
	Overburden <1 m	1

[8] Based on Madden and O'Hara, 2016

E. Karst Feature Density (within 250 m)	>4 features	4
	3-4 features	3
	1-2 features	2
	No features	1
F. Direct Interaction with Karst Feature	Within feature footprint	3
	No interaction	1

The calculated hazard scores were subsequently assigned to hazard categories reflecting the likelihood that karst-related ground conditions may influence development. The classifications are intended to guide engineering design requirements and determine the level of mitigation or additional investigation that may be required as part of the construction phase. Summary hazard classes are identified below in Table 4-2.

Table 4-2 Hazard tables

Hazard Rating	Description	Development Implication
Low 0-10	Little evidence of karstification	Normal design and construction practices
Moderate 10-40	Evidence of weathered limestone or nearby karst features	Standard geotechnical review and Karst Protocol
High 40-80	Significant karst indicators present within footprint	Additional targeted investigation and design measures
Very High >80	Confirmed significant karst features or voids within footprint	Avoidance preferred or major engineering mitigation required

Summary details for the turbines and proposed 110 kV substation is included below in Table 4-3.

Table 4-3 Proposed permanent structures (Turbine and 110kV Substation) Karst Risk Screening[9]

Location	Rockhead Depth	Overburden Type	Karst Susceptibility	Assessment
T1	2.1 m	Sandy silt and limestone gravel	Moderate	Limestone encountered at shallow depth. Limited cover thickness and possibility of irregular rockhead. Doline located within 60 m of turbine. No evidence of cavities or open karst voids during drilling.

[9] Key infrastructure locations – no karst features within 250 m of compounds or borrow pits

Location	Rockhead Depth	Overburden Type	Karst Susceptibility	Assessment
T2	c 3 m	Gravelly silt	Low	Limestone at shallow depth based on trial pits and geophysics. Competent bedrock at turbine.
T3	2.3 m	Sandy gravel	Low	Granular soil deposits. No weathered limestone or cavities identified. Competent bedrock at turbine.
T4	1.1 m	Sandy silt to weathered limestone	Low	Shallow limestone and weathered rock beneath very thin cover. Competent bedrock at turbine.
T5	Limestone boulders/bedrock at 0.8 m	Gravel/Boulders	Low	Shallow limestone and weathered rock beneath very thin cover. Competent bedrock at turbine.
T6	Bedrock at 2.35 m	Sandy silt with cobbles	Low	Shallow limestone and weathered rock beneath very thin cover. Competent bedrock at turbine based on geophysics.
T7	3.1 m	Limestone gravel over weathered limestone	Low	Weathered limestone profile identified. Rockhead is deeper. Competent bedrock at turbine based on geophysics.
T8	Not proven to 1.7 m	Silty sand and gravel	Low	Granular deposits. No evidence of weathered rock or dissolution features within GI. Competent bedrock at turbine based on geophysics.
T9	Weathered rock at 2.9 m; limestone at 4.9 m	Limestone gravel over weathered limestone	Low	Weathered rock profile indicates prolonged dissolution/weathering processes. Deeper competent rock.
T10	Weathered limestone from 4.1 m	Limestone gravel	Moderate	Thick zone of weathered limestone between 4.1 m and 7.3 m. The weathered limestone encountered is described as: Very strong to strong limestone; Point load strengths of approximately 4.1-4.5 MPa Is(50), indicating strong rock material. One karst feature within 250 m.

Location	Rockhead Depth	Overburden Type	Karst Susceptibility	Assessment
T11	Bedrock at 0.7 m	Gravel	Low	Shallow granular deposits only. No karst indicators in GI.
T12	Bedrock at 0.8 m	Gravelly silt	Low	No karst indicators in GI.
T13	Bedrock at 2.7 m	Sandy silt over limestone gravel	Moderate	Similar to T1. Shallow limestone and relatively thin overburden
110 kV Substation	Bedrock >1.6m	Sandy silt over limestone gravel	Low	Similar to T1. Shallow limestone and relatively thin overburden

The assessment matrix below in Table 4-4 demonstrates that areas classified as medium karst susceptibility are primarily associated with shallow limestone bedrock, localised weathering and limited overburden thickness rather than confirmed karst voids or active dissolution features. No cavities, open conduits or collapse features were encountered during drilling, trial pitting or geophysical investigations.

Consequently, the identified risks are considered suitable for construction of turbine foundations and hardstands through conventional geotechnical design and the implementation of the Karst Encounter Protocol during construction.

Table 4-4 Karst Risk Assessment Matrix

Location	A	B	C	D	E	F	Hazard Score	Risk Category
Location	Bedrock type[10]	Geological faults	Overburden thickness	Overburden thickness	Karst feature density – within 250 m	Karst feature density - direct		
T1	2	1	3	1	2	1	12	Moderate
T2	2	1	3	1	1	1	6	Low
T3	2	1	3	1	1	1	6	Low
T4	2	1	3	1	1	1	6	Low
T5	2	1	3	1	1	1	6	Low
T6	2	1	3	1	1	1	6	Low
T7	2	1	3	1	1	1	6	Low
T8	2	1	3	1	1	1	6	Low
T9	2	1	3	1	1	1	6	Low
T10	2	1	3	1	2	1	12	Moderate
T11	2	1	3	1	1	1	6	Low
T12	2	1	3	1	1	1	6	Low
T13	2	1	3	1	2	1	12	Moderate
110 kV Substation	2	1	3	1	1	1	6	Low

[10] See Tables 4-1 to 4-3

An infrastructure-specific review was undertaken to determine whether any element of the proposed wind farm site and 110 kV substation could directly interact with identified karst features or create pathways that may adversely affect the karst environment.

5. MITIGATION MEASURES

5.1 EMBEDDED DESIGN MITIGATION

Karst risk has been addressed at the earliest stages of the project through the iterative site design process. The findings of the desk study, site walkovers, ground investigations and geophysical surveys were used to inform the siting of key infrastructure, with turbines, borrow pit, the proposed 110 kV substation and other permanent infrastructure positioned to avoid identified karst features. In addition, a 30 m buffer around karst features was applied to further limit the potential for karst.

The four mapped dolines and the identified losing stream have been excluded from direct disturbance, and no infrastructure is proposed within these features. Ground investigation results did not identify subsurface cavities, significant dissolution features or evidence of instability beneath the proposed infrastructure locations, further reducing potential geotechnical and hydrogeological risks. Through the application of this avoidance-based design approach, potential interactions with the karst environment have been minimised at source, significantly reducing the requirement for engineering intervention and representing the primary mitigation measure incorporated into the project design.

5.2 CONSTRUCTION PHASE MITIGATION

The findings of the assessment indicate that the majority of the proposed wind farm site/substation can be classed as having a low to medium karst risk. In these locations, it is considered that significant karst development is unlikely, and unstable ground and significant cavities are not anticipated. All proposed infrastructure has been sited to avoid areas of very high karst hazard. Best practice measures as detailed in the Karst Protocol will be implemented if any karst feature is encountered during construction – See Appendix A.

All earthworks will be designed by a suitably qualified Geotechnical Engineer during the detailed design stage and informed by a detailed confirmatory ground investigation. This investigation will include intrusive methods, such as trial pitting and borehole drilling, with a specified suite of in-situ and geotechnical laboratory testing to further assess the engineering characteristics of the infrastructure locations.

Portions of the proposed wind farm site have been classed as having moderate karst hazard, based on professional judgement following site investigation and desktop analysis and proximity to features. In these areas, specific mitigation measures may be required, i.e micropiles and geogrid reinforcement. The following ground investigation works will be carried out at infrastructure locations identified as having medium or greater karst risk:

- Rotary core boreholes to confirm rockhead depth and quality.
- Geophysical Surveying to detect voids and solution features, including:
  - Electrical Resistivity Tomography (ERT)
  - Microgravity; and
  - Seismic Refraction
- Trial pits and dynamic probing to assess near-surface variability and soils.

Mitigation will be implemented at detailed design stage to reduce the karst risk:

- For the turbine foundations, a geotechnical investigation will be carried out at each location prior to works commencing. Surveying will include the drilling of boreholes by rotary core to depth within competent bedrock to determine the strength of rock and assess the potential for karst or weathered rock at each location by a qualified geotechnical engineer to inform foundation design. Micropiles will only be undertaken if geogrid and backfilling is not suitable in areas of weak rock to ensure long term stability, and that the turbine loads are taken to intact rock. A larger number of small piles or micropiles designed with rock sockets to transfer loads via skin friction are preferred in karst landscapes (Rutty & Jennings, 2012, Traylor et al., 2002), rather than a smaller number of large piles relying on end bearing. It is recommended that piles are designed on the basis of transferring loads via skin friction to a rock socket.
- For access tracks and hardstandings, the karst feature inspection protocol documented by Madden & O'Hara (2016), included in Appendix A, is routinely followed for construction of linear infrastructure in karst landscapes. A similar karst feature inspection protocol will be developed and followed during detailed design.
- Where small-scale dissolution and voiding are encountered at turbine foundations during detailed ground investigation, mitigation strategy is the use of drilled or grouted piles. The use of piles transfers structural loads to competent rock beneath karst-affected zones. This approach bypasses voids and weak soils, reducing the risk of differential settlement or collapse.
- Ground stabilisation measures to be employed include compaction, grouting/stabilisation, geotextile or utilising raft foundations. Where weathered limestone or karst is encountered at formation level, the feature will be mapped in detail. Each feature and associated mitigation measure will be documented and included in the safety file. The stabilisation measures will be approved by a geotechnical engineer. Where infilling or grouting is undertaken works will be supervised by a suitably qualified hydrogeologist to ensure there is no effect on groundwater.
- Waltham et al. (2005) outline an approach for the remediation of shallow karst features. This methodology involves adding coarse granular fill to the base of karst feature, and progressive backfilling upwards with progressively finer granular fill. All backfill is to be placed in layers 150 mm deep and compacted. Soil around the doline/sinkhole is to be excavated to a radius of 3-5m, before being replaced and compacted with or without incorporation of anchored geogrid. This methodology has been used effectively on Irish road projects in similar karst terrains in East Galway (Madden and O'Hara, 2016).

  This methodology is applicable to the proposed wind farm site access tracks and shall be implemented if small scale sinkhole features (<5m in depth) are encountered beneath access tracks. No karst features were observed in line with any access track or other proposed infrastructure.

- Where construction takes place in areas of high karst hazard, and if karstic features are identified elsewhere during construction, the following measures shall be implemented:
    - Access tracks will incorporate geogrid-reinforced bridging layers over areas identified as having potential voids or collapse-prone soils.
    - Crane hardstands will be designed with enhanced bridging layers to accommodate high point loads and dynamic stresses.
- Proper drainage control is therefore essential to maintain the stability of foundations and prevent erosion of fill materials. All works will be supervised by a suitably qualified geotechnical engineer or hydrogeologist.

6. CONCLUSION AND RECOMMENDATIONS

The proposed wind farm site is located within a Regionally Important karstified limestone aquifer with bedrock at or close to the surface. Four enclosed depressions and one losing stream were mapped at the proposed wind farm site.

The combination of desk studies, aerial photograph interpretation, site walkovers, geophysical surveys and intrusive ground investigations indicates that significant karst development is limited within the proposed infrastructure areas. No mapped or verified karst features will be directly affected by the development, and no subsurface cavities were encountered during ground investigations. The principal residual risks relate to potential contamination pathways and localised instability associated with weathered limestone zones. Subject to implementation of the drainage design, groundwater protection measures, hydrogeological supervision and Karst Protocol, the residual effects on the karst environment are assessed as not significant. Following the implementation of mitigation measures, the residual risk at each infrastructure location is low.

The assessment incorporates the adopted infrastructure layout, karst avoidance measures and proposed drainage controls. The resulting residual risks are summarised in Table 6-1.

Table 6-1 Karst Infrastructure-Specific Karst Screening Matrix

Infrastructure Element	Presence of Karst Features within Footprint	Residual Risk Rating
Turbine Foundations	None identified, Avoidance of karst features through design	Low
Hardstands	None identified	Low
Borrow Pit	No karst features; shallow groundwater possible	Low
Wind Farm Access Tracks	None identified. Avoidance of karst features through design	Low
110 kV Substation	None identified, Doline approximately 200 m away	Low
Construction Compound	None identified, Avoidance of karst features through design	Low

Following implementation of the proposed mitigation measures, residual risks have been classified according to the potential for interaction with karst features and groundwater pathways. The risk categories provide a consistent framework for evaluating the significance of residual effects and demonstrate the effectiveness of the embedded and proposed mitigation measures. Table 6-1 presents the residual risk classification criteria applied in this assessment

A post-construction monitoring plan will be implemented, including visual inspections, settlement monitoring, and geophysical re-surveys. This proactive approach ensures that any emerging issues are detected and addressed promptly, maintaining the long-term integrity of the wind farm infrastructure.

A suitably qualified hydrogeologist and engineering geologist shall provide supervision during excavation of turbine foundations, borrow pit development and other deep excavations in areas underlain by limestone bedrock. Should evidence of karstification, dissolution features, voids or unexpectedly high groundwater inflows be encountered, works shall cease within the affected area and the Karst Protocol shall be implemented. Any remedial measures, including stabilisation or grouting, shall be implemented to avoid adverse impacts on the hydrogeological regime.

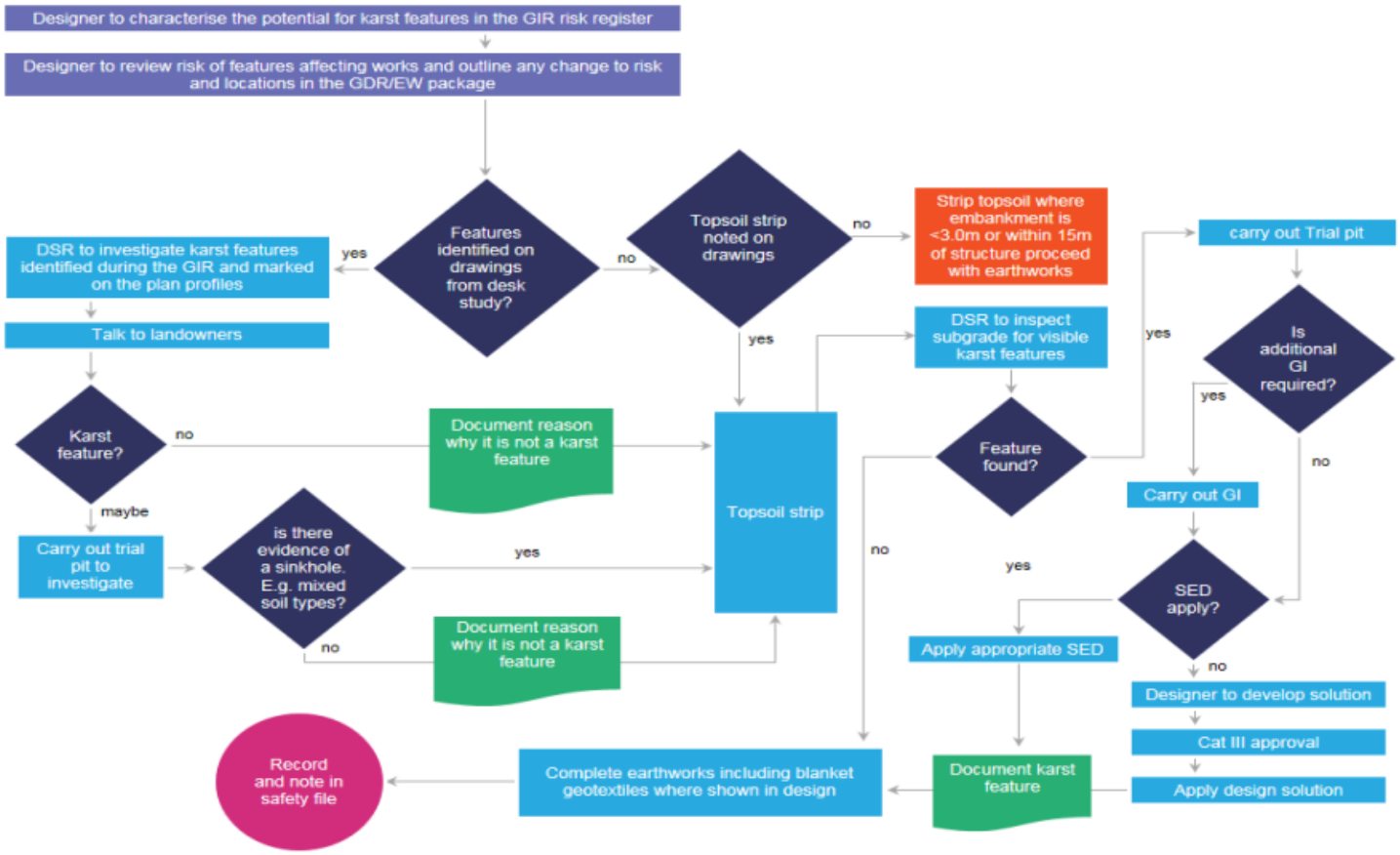
Monitoring shall include routine inspections of excavations, drainage infrastructure, settlement ponds and identified karst features located in proximity to the proposed wind farm site and 110 kV substation. Groundwater levels within monitoring wells shall be recorded during major excavation activities and following significant rainfall events. Any changes in groundwater response shall trigger investigation by a suitably qualified hydrogeologist or geotechnical engineer.

7. REFERENCES

- Madden, P. & Hara, M. (2014). Karst Risk Assessment Protocol for Development Projects
- Madden and Hara (2016) The treatment of karst features encountered during road construction in County Galway
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- Traylor, R., Cadden, A.W., Bruce, D. A. (2002) High Capacity Micropiles in Karst: Challenges and Opportunities
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APPENDIX A – KARST PROTOCOL

Madden and Hara (2016)



APPENDIX B EXAMPLE CONSTRUCTION METHOD

