

Appendix 7.4: Peat Landslide Hazard and Risk Assessment

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Consulting Report

Appendix 7.4 - Peat Landslide Hazard and Risk Assessment
An Càrr Dubh Wind Farm

Argyll & Bute
Car Duibh Wind Farm Ltd

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Prepared for
Land Use Consultants



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1. INTRODUCTION

1.1. Background

Car Duibh Wind Farm Ltd (the Applicant) is seeking consent under Section 36 of the Electricity Act 1989 for construction of the An Càrr Dubh Wind Farm, Argyll & Bute (hereafter the 'Proposed Development').

The Site boundary for the Proposed Development lies approximately 1 km to the west of Inveraray and 2.5 km east of Dalavich and is approximately 16 km² (c. 1,600ha) in area (Plate 1.1). The closest turbines are located approximately 6 km to the NW of Inveraray (T1) and approximately 4.5 km to the east of Dalavich (T13). The Site is bordered to the north and south by open peatlands and to the west and east by commercial forestry plantations.

The Proposed Development is described in **Chapter 4: Project Description** of the EIA Report.

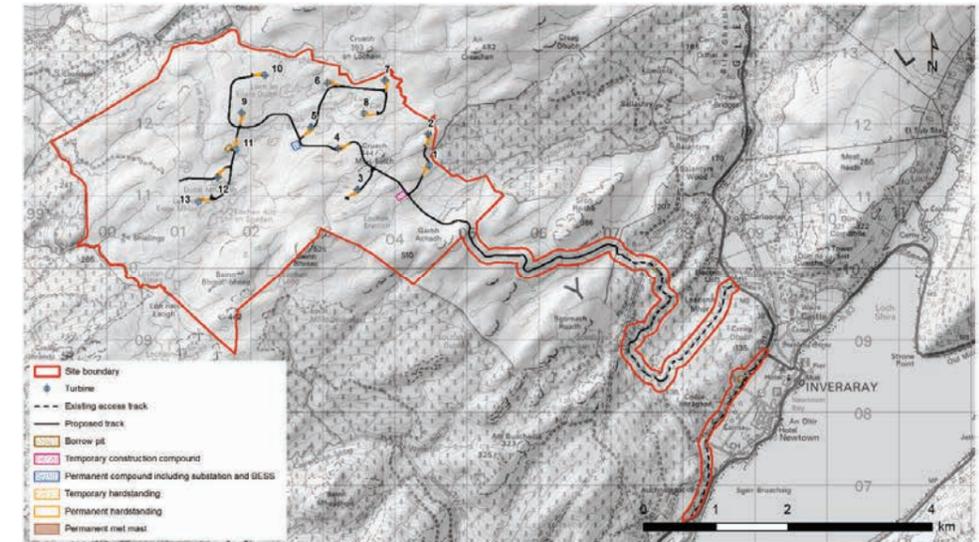


Plate 1.1 Proposed location of the An Càrr Dubh wind farm

The Scottish Government Best Practice Guidance (BPG) provides a screening tool to determine whether a peat landslide hazard and risk assessment (PLHRA) is required (Scottish Government, 2017). This is in the form of a flowchart, which indicates that where blanket peat is present, slopes exceed 2° and proposed infrastructure is located on peat, a PLHRA should be prepared. These conditions exist at the Proposed Development site and therefore a PLHRA is required. This PLHRA Report is provided as an Appendix to the Environmental Impact Assessment (EIA) Report for the Proposed Development.

1.2. Scope of Work

The scope of the PLHRA is as follows:

- Characterise the peatland geomorphology of the Site to determine whether prior incidences of instability have occurred and whether contributory factors that might lead to instability in the future are present across the Site.

- Determine the likelihood of a future peat landslide under natural conditions and in association with construction activities associated with the Proposed Development.
- Identify potential receptors that might be affected by peat landslides, should they occur, and quantify the associated risks.
- Provide appropriate mitigation and control measures to reduce risks to acceptable levels such that the Proposed Development is developed safely and with minimal risks to the environment.

The contents of this PLHRA have been prepared in accordance with the BPG, noting that the guidance “*should not be taken as prescriptive or used as a substitute for the developer’s [consultant’s] preferred methodology*” (Scottish Government, 2017). The first edition of the Scottish Government Best Practice Guidance (BPG) was issued in 2007 and provided an outline of expectations for approaches to be taken in assessing peat landslide risks on wind farm sites. After ten years of practice and industry experience, the BPG was reissued in 2017, though without fundamental changes to the core expectations. A key change was to provide clearer steer on the format and outcome of reviews undertaken by the Energy Consents Unit (ECU) checking authority and related expectations of report revisions, should they be required.

In section 4.1 of the BPG, the key elements of a PLHRA are highlighted, as follows (Scottish Government, 2017):

- An assessment of the character of the peatland within the application boundary including thickness and extent of peat, and a demonstrable understanding of site hydrology and geomorphology.
- An assessment of evidence for past landslide activity and present-day instability e.g. pre-failure indicators.
- A qualitative or quantitative assessment of the potential for or likelihood of future peat landslide activity (or a landslide susceptibility or hazard assessment).
- Identification of receptors (e.g. habitats, watercourses, infrastructure, human life) exposed to peat landslide hazards; and
- A site-wide qualitative or quantitative risk assessment that considers the potential consequences of peat landslides for the identified receptors.

Section 1.3 describes how this report addresses this indicative scope. Because the majority of the access track into the Site from the public road is an upgraded forestry track away from the open fell, the spatial scope of the assessment is limited to the open fell area and probing extent where the turbines and associated new infrastructure are located (see Section 3.5 for more information).

1.3. Report Structure

This report is structured as follows:

- Section 2 gives context to the landslide risk assessment methodology through a literature based account of peat landslide types and contributory factors, including review of any published or anecdotal information available concerning previous instability at or adjacent to the Site.
- Section 3 provides a site description based on desk study and site observations, including consideration of aerial or satellite imagery, digital elevation data, geology and peat depth data.

- Section 4 describes the approach to and results of an assessment of peat landslide likelihood under both natural conditions and in association with construction of the Proposed Development.
- Section 5 describes the approach to and results of a consequence assessment that determines potential impacts on site receptors and the associated calculated risks.
- Section 6 provides mitigation and control measures to reduce or minimise these risks prior to, during and after construction.

Assessments within the PLHRA have been undertaken alongside assessments for the Peat Management Plan (EIA Report Appendix 7.3) and have been informed by results from the Peat Survey (EIA Report Appendix 7.2). Where relevant information is available elsewhere in the EIA Report and associated figures and appendices, this is referenced in the text rather than repeated in this report.

1.4. Approaches to assessing peat instability for the Proposed Development

This report approaches assessment of peat instability through both a qualitative contributory factor-based approach and via more conventional stability analysis (through limit equilibrium or Factor of Safety (FoS) analysis). The advantage of the former is that many observed relationships between reported peat landslides and ground conditions can be considered together where a FoS is limited to consideration of a limited number of geotechnical parameters. The disadvantage is that the outputs of such an approach are better at illustrating relative variability in landslide susceptibility across a site rather than absolute likelihood.

The advantage of the FoS approach is that clear thresholds between stability and instability can be defined and modelled numerically, however, in reality, there is considerable uncertainty in input parameters and it is a generally held view that the geomechanical basis for stability analysis in peat is limited given the nature of peat as an organic, rather than mineral soil.

To reflect these limitations, both approaches are adopted and outputs from each approach integrated in the assessment of landslide likelihood. Plate 1.2 shows the approach:

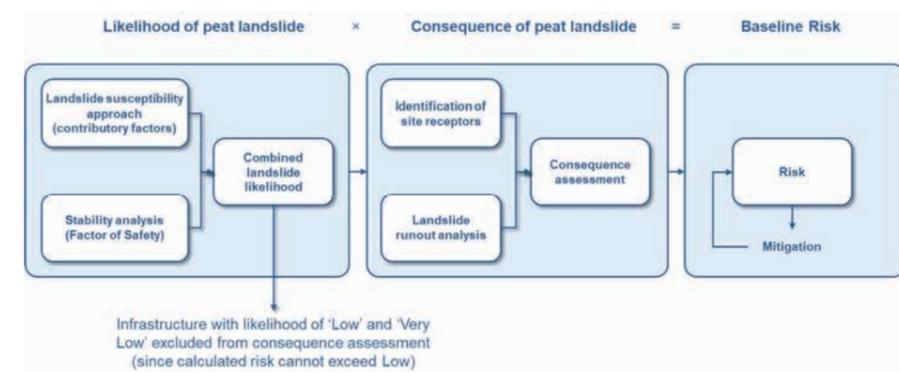


Plate 1.2 Risk assessment approach

2. BACKGROUND TO PEAT INSTABILITY

2.1. Peat Instability in the UK and Ireland

This section reviews published literature to highlight commonly identified landscape features associated with recorded peat landslides in the UK and Ireland. This review forms the basis for identifying similar features at the Proposed Development and using them to understand the susceptibility of the site to naturally occurring and human induced peat landslides.

Peat instability, or peat landslides, are a widely documented but relatively rare mechanism of peatland degradation that may result in damage to peatland habitats, potential losses in biodiversity and depletion of peatland carbon stores (Evans & Warburton, 2007). Public awareness of peat landslide hazards increased significantly following three major peat landslide events in 2003, two of which had natural causes and one occurring in association with a wind farm.

On 19th September 2003, multiple peat landslide events occurred in Pollatomish (Co. Mayo, Ireland; Creighton and Verbruggen, 2003) and in Channerwick in the Southern Shetland Islands (Mills et al, 2007). Both events occurred in response to intense rainfall, possibly as part of the same large scale large-scale weather system moving northeast from Ireland across Scotland. The former event damaged several houses, a main road and washed away part of a graveyard. Some of the landslides were sourced from areas of turbarry (peat cutting) with slabs of peat detaching along the cuttings. The landslides in Channerwick blocked the main road to the airport and narrowly missed traffic using the road. Watercourses were inundated with peat, killing fish inland and shellfish offshore (Henderson, 2005).

In October 2003, a peat failure occurred on an afforested wind farm site in Derrybrien, County Galway, Ireland, causing disruption to the site and large-scale fish kill in the adjoining watercourses (Lindsay and Bragg, 2004).

The Derrybrien event triggered interest in the influence of wind farm construction and operation on peatlands, particularly in relation to potential risks arising from construction induced peat instability. In 2007, the (then) Scottish Executive published guidelines on peat landslide hazard and risk assessment in support of planning applications for wind farms on peatland sites. While the production of PLHRA reports is required for all Section 36 energy projects on peat, they are now also regarded as best practice for smaller wind farm applications. The guidance was updated in 2017 (Scottish Government, 2017).

Since then, a number of peat landslide events have occurred both naturally and in association with wind farms (e.g. Plate 2.1). In the case of wind farm sites, these have rarely been reported, however landslide scars of varying age are visible in association with wind farm infrastructure on Corry Mountain, Co. Leitrim, at Sonnagh Old Wind Farm, Co. Galway (near Derrybrien; Cullen, 2011), and at Corkey Wind Farm, Co. Antrim. In December 2016, a plant operator was killed during excavation works in peat at the Derrysallagh wind farm site in Co. Leitrim (Flaherty, 2016) on a plateau in which several published examples of instability had been previously reported. Peat landslides have also been reported within the site of the under-construction Viking Wind Farm on Shetland (Shetland News, 2022) in association with construction works. A pre-construction landslide was reported within the same site in 2015, but not in association with construction (The Shetland Times, 2015).

Other recent natural events include another failure in Galway at Clifden in 2016 (Irish News, 2016), Cushendall, Co. Antrim (BBC, 2014), in the Glenelly Valley, Co. Tyrone in 2017 (BBC, 2018), Drumkeeran in Co. Leitrim in July 2020 (Irish Mirror, 2020) and Benbrack in Co Cavan in July 2021

(The Anglo-Celt, 2021). Noticeably, the vast majority of reported failures since 2003 have occurred in Ireland and Northern Ireland, with the one reported Scottish example occurring on the Shetland Islands, an area previously associated with peat instability.

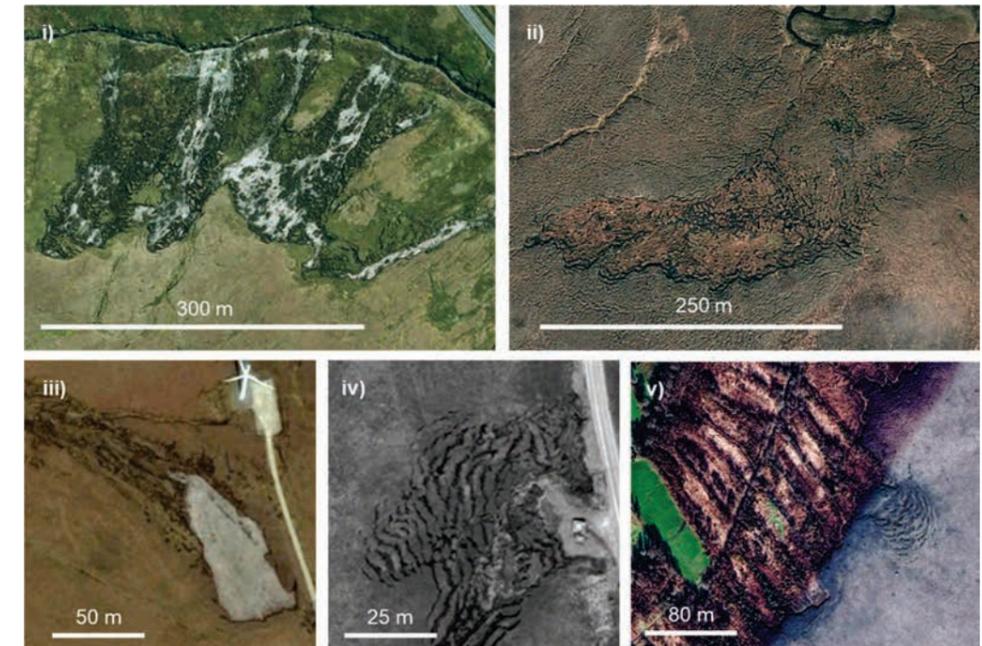


Plate 2.1 Characteristic peat landslide types in UK and Irish peat uplands: Top row - natural failures: i) multiple peat slides with displaced slabs and exposed substrate, ii) retrogressive bog burst with peat retained within the failed area; Bottom row - failures possibly induced by human activity: iii) peat slide adjacent to turbine foundation, iv) spreading around foundation, v) spreading upslope of cutting

This section of the report provides an overview of peat instability as a precursor to the site characterisation in Section 3 and the hazard and risk assessment provided in Sections 4 and 5. Section 2.2 outlines the different types of peat instability documented in the UK and Ireland. Section 2.3 provides an overview of factors known to contribute to peat instability based on published literature.

2.2. Types of Peat Instability

Peat instability is manifested in a number of ways (Dykes and Warburton, 2007) all of which can potentially be observed on site either through site walkover or remotely from high resolution aerial photography:

- **minor instability:** localised and small-scale features that are not generally precursors to major slope failure and including gully sidewall collapses, pipe ceiling collapses, minor slumping along diffuse drainage pathways (e.g. along flushes); indicators of incipient instability including development of tension cracks, tears in the acrotelm (upper vegetation mat), compression ridges, or bulges / thrusts (Scottish Government, 2017); these latter features may be warning signs of larger scale major instability (such as landsliding) or may simply represent a longer term response of the hillslope to drainage and gravity, i.e. creep.

- **major instability:** comprising various forms of peat landslide, ranging from small scale collapse and outflow of peat filled drainage lines/gullies (occupying a few-10s cubic metres), to medium scale peaty-debris slides in organic soils (10s to 100s cubic metres) to large scale peat slides and bog bursts (1,000s to 100,000s cubic metres).

Evans and Warburton (2007) present useful contextual data in a series of charts for two types of large-scale peat instability – peat slides and bog bursts. The data are based on a peat landslide database compiled by Mills (2002) which collates site information for reported peat failures in the UK and Ireland. Separately, Dykes and Warburton (2007) provide a more detailed classification scheme for landslides in peat based on the type of peat deposit (raised bog, blanket bog, or fen bog), location of the failure shear surface or zone (within the peat, at the peat-substrate interface, or below), indicative failure volumes, estimated velocity and residual morphology (or features) left after occurrence.

For the purposes of this assessment, landslide classification is simplified and split into three main types, typical examples of which are shown in Plate 2.1. Dimensions, slope angles and peat depths are drawn from charts presented in Evans and Warburton (2007). The term “peat slide” is used to refer to large-scale (typically less than 10,000 of cubic metres) landslides in which failure initiates as large rafts of material which subsequently break down into smaller blocks and slurry. Peat slides occur ‘top-down’ from the point of initiation on a slope in thinner peats (between 0.5 m and 1.5 m) and on moderate slope angles (typically 5°-15°, see Plate 2.2).

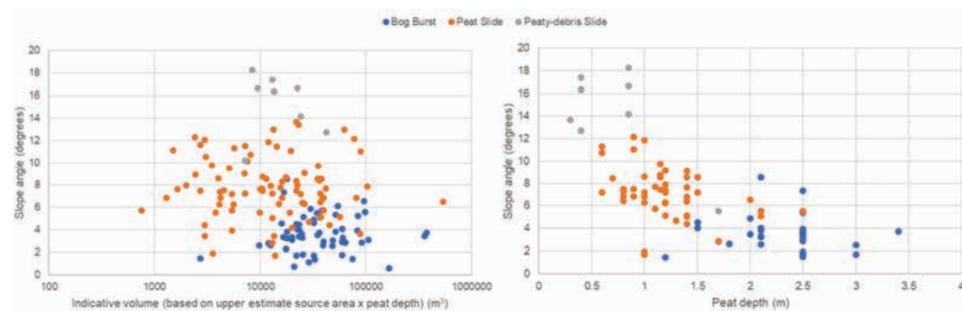


Plate 2.2 Reported slope angles and peat depths associated with peat slides and bog bursts (from literature review of locations, depths and slope angles, after Mills, 2002)

The term “bog burst” is used to refer to very large-scale (usually greater than 10,000 of cubic metres) spreading failures in which the landslide retrogresses (cuts) upslope from the point of failure while flowing downslope. Peat is typically deeper (greater than 1.0m and up to 10m) and more amorphous than sites experiencing peat slides, with shallower slope angles (typically 2°-5°). Much of the peat displaced during the event may remain within the initial failure zone.

The term “peaty soil slide” is used to refer to small-scale (1,000s of cubic metres) slab-like slides in organic soils (i.e. they are <0.5 m thick). These are similar to peat slides in form, but far smaller and occur commonly in UK uplands across a range of slope angles (Dykes and Warburton, 2007). Their small size means that they often do not affect watercourses and their effect on habitats is minimal.

Few if any spreading failures in peat (i.e. bog bursts) have been reported in Scotland, with only one or two unpublished examples in evidence on the Isle of Lewis and Caithness (e.g. Bowes, 1960).

There are no published failures or news reports of landslides in proximity to the Proposed Development.

2.2.1. Factors Contributing to Peat Instability

Peat landslides are caused by a combination of factors – triggering factors and preconditioning factors (Dykes and Warburton, 2007; Scottish Government, 2017). Triggering factors have an immediate or rapid effect on the stability of a peat deposit whereas preconditioning factors influence peat stability over a much longer period. Only some of these factors can be addressed by site characterisation.

Preconditioning factors may influence peat stability over long periods of time (years to hundreds of years), and include:

- Impeded drainage caused by a peat layer overlying an impervious clay or mineral base (hydrological discontinuity).
- A convex slope or a slope with a break of slope at its head (concentration of subsurface flow).
- Proximity to local drainage, either from flushes, pipes or streams (supply of water).
- Connectivity between surface drainage and the peat/impervious interface (mechanism for generation of excess pore pressures).
- Artificially cut transverse drainage ditches, or grips (elevating pore water pressures in the basal peat-mineral matrix between cuts, and causing fragmentation of the peat mass).
- Increase in mass of the peat slope through peat formation, increases in water content or afforestation.
- Reduction in shear strength of peat or substrate from changes in physical structure caused by progressive creep and vertical fracturing (tension cracking or desiccation cracking), chemical or physical weathering or clay dispersal in the substrate.
- Loss of surface vegetation and associated tensile strength (e.g. by burning or pollution induced vegetation change).
- Increase in buoyancy of the peat slope through formation of sub-surface pools or water-filled pipe networks or wetting up of desiccated areas.
- Afforestation of peat areas, reducing water held in the peat body, and increasing potential for formation of desiccation cracks which are exploited by rainfall on forest harvesting.

Triggering factors are typically of short duration (minutes to hours) and any individual trigger event can be considered as the ‘straw that broke the camel’s back’:

- Intense rainfall or snowmelt causing high pore pressures along pre-existing or potential rupture surfaces (e.g. between the peat and substrate).
- Rapid ground accelerations (e.g. from earthquakes or blasting).
- Unloading of the peat mass by fluvial incision or by artificial excavations (e.g. cutting).
- Focusing of drainage in a susceptible part of a slope by alterations to natural drainage patterns (e.g. by pipe blocking or drainage diversion).
- Loading by plant, spoil or infrastructure.

External environmental triggers such as rainfall and snowmelt cannot be mitigated against, though they can be managed (e.g. by limiting construction activities during periods of intense rain). Unloading of the peat mass by excavation, loading by plant and focusing of drainage can be

managed by careful design, site specific stability analyses, informed working practices and monitoring.

2.2.2. Consequences of Peat Instability

Both peat slides and bog bursts have the potential to be large in scale, disrupting extensive areas of blanket bog and with the potential to discharge large volumes of material into watercourses. A key part of the risk assessment process is to identify the potential scale of peat instability should it occur and identify the receptors of the consequences. Potential sensitive receptors of peat failure are:

- The development infrastructure and turbines (damage to turbines, tracks, substation, etc).
- Site workers and plant (risk of injury / death or damage to plant).
- Wildlife (disruption of habitat) and aquatic fauna.
- Watercourses and lochs (particularly associated with public water supply).
- Site drainage (blocked drains / ditches leading to localised flooding / erosion).
- Visual amenity (scarring of landscape).

While peat failures may cause visual scarring of the peat landscape, most peat failures revegetate fully within 50 to 100 years and are often difficult to identify on the ground after this period of time (Feldmeyer-Christe and Kùchler, 2002; Mills, 2002). Typically, it is short-term (seasonal) effects on watercourses or impacts on public water supply that are the primary concern.

3. DESK STUDY

3.1. Topography

The Proposed Development straddles the hills to the north of Beinn Bhreac (526 m) and surrounds Cruach Mhic Eoich (444 m), the access track falling to the southeast into commercial forestry above Inveraray before connecting to the public road. Much of the main turbine area lies over strongly northeast-southwest aligned ridges with intervening troughs (Figure 7.4.1). This topography has a strong influence on the position of major water bodies and deeper peat deposits (see Plate 3.1 below and section 3.5).

In the troughs and on the ridge spurs, slope angles are relatively low (typically <math><5^\circ</math>) but these rapidly increase over the steeper sideslopes of the ridges, in particular as the proposed access track approaches the forest margin, with slopes frequently exceeding

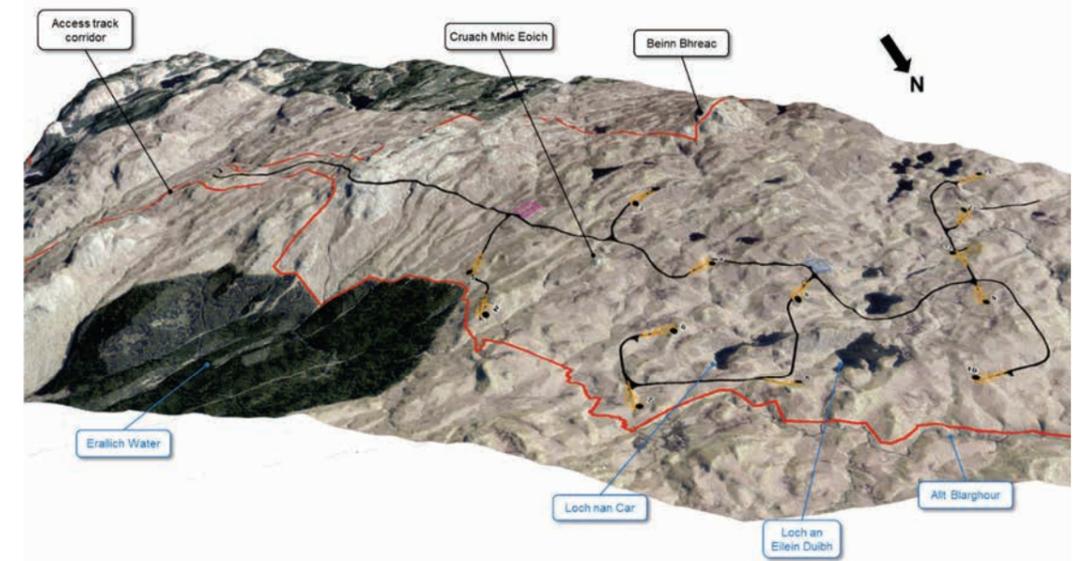


Plate 3.1 Perspective view of Proposed Development (note 2x vertical exaggeration)

3.2. Geology

Figure 7.4.3 shows the solid geology of the Site mapped from 1:50,000 scale publicly available BGS digital data and indicates the majority of the main turbine area to be underlain by northeast-southwest aligned aligned bands of Crinan Grit formation quartzite (previously marine sedimentary rocks that have subsequently metamorphosed) and Dalradian Supergroup gabbro and metamicrogabbro (igneous rocks that have undergone metamorphism). The steepening slopes on the access track pass over a silica-rich igneous intrusion of Scottish Highland Siluro-Devonian Calc-Alkaline with batholiths, pluton sills and dykes. In the far north of the Site (underlying proposed Turbine 10), metalimestones and pelites of the Tayvalich Slate and Limestone formation are present.

Figure 7.4.3 also shows the superficial geology of the Site mapped from 1:50,000 scale BGS digital data, with Devensian till diamicton present around the northern margin of the Proposed Development

and hummocky glacial diamicton of sand and gravels in the west of the Site. No superficial peat deposits are shown on the mapping.

The Carbon and Peatland 2016 Map (shown as an inset on Figure 7.4.5) predicts the entirety of the open hill area to comprise Class 2 nationally important carbon-rich soils, deep peat, and priority peatland habitat (i.e., land covered by peat-forming vegetation or vegetation associated with peat formation). Areas under forestry are shown as Class 5, with no peatland habitat recorded, but soils are considered to be carbon-rich and deep peat is present.

There are no SSSIs within the Proposed Development area and therefore no Regionally Important Geological Sites (RIGS) or Local Geodiversity Sites (LDS).

3.3. Hydrology

The Proposed Development hosts a number of lochans of varying size (Figure 7.4.4) with interconnecting minor water bodies running along trough floors, typically on northeast-southwest alignments in keeping with the prevailing geologically dominated topography.

Minor parallel tributaries of the Erallich Water drain east from the access track corridor towards the River Aray, classified as of Moderate ecological health status by SEPA (see Chapter 7 of the EIA Report).

The Allt Blarghour drains the northern limits of the Proposed Development towards Loch Awe collecting a small number of minor tributaries in the vicinity of Loch an Eilein Duibh and Loch nan Car. This river was also classified by SEPA as of Moderate status. A small hydroelectric power scheme is located on the Allt Blarghour, with its intake located to the north of proposed Turbine 10.

The Kames River drains the west of the Proposed Development and is fed by parallel minor tributaries falling from Lochan Dubh Mhuilinn, Lochan Eisce Mhoir and Lochan Allt an Sgadain (in the vicinity of Turbine 13). The river ultimately discharges to Loch Awe, and the river is classified as of Moderate status.

The Douglas Water drains to the southeast towards Loch Fyne from the southern boundary of the Proposed Development collecting from a series of tributaries to the south of Beinn Bhreac. This river is also classified as of Moderate status.

Many of the within-site watercourses are of relatively limited capacity, and unlikely to be able to convey landslide debris a long distance downstream, and in many cases, lochans may form the end point of any downstream transmission.

There are no surface water related designations within the Site, however, the Site falls within a drinking water catchment where a Scottish Water abstraction is located. The Douglas Water supplies the Inveraray Water Treatment Works (WTW), although there is no proposed infrastructure upgradient of the water abstraction points (see Table 7.6, Chapter 7 of the EIA Report).

Much of the Site has been subject to drainage by artificial moor drains / grips (see Figure 7.4.4). Photographs of typical hydrological features, including drains, water bodies and watercourses are shown in Plates 3a-e below.

3.4. Land Use

The majority of the Proposed Development is used for rough grazing of sheep, with deer also present. Commercial forestry plantation is present on the lower slopes. There are no peat cuttings on the Site and no major quarries.



Plate 3.1 a) a partially recovered moor drain infilled by *Sphagnum*, b) one of a number of parallel linear tributaries to the Erallich River in the vicinity of Turbine 1, c) the Eas an Amair (a tributary of Allt Blarghour) to the south of Turbine 11, d) lochans in the central part of the main turbine area, e) active drains (arrowed)

3.5. Peat Depth and Character

Peat depth probing was undertaken in 2 phases in accordance with Scottish Government (2017) guidance:

- A total of 5,363 probes were collected across Phase 1 (100 m grid, between March and August 2021) and Phase 2 (detailed infrastructure-specific probing, between January and March 2022, and with some additional probing in October 2022).
- 39% of probes recorded depths <50 cm and therefore recorded organic soils (rather than peat), although organic soils may still support priority peatland habitats.
- Peat exceeded 4.9 m in depth at a number of locations across the Site, however these areas have been entirely avoided.
- 18 cores were taken across the Site (locations detailed on Figure 7.2 of the EIA Report) with substrate corresponding to bedrock in around 50% of locations.

A peat survey report (Appendix 7.2) provides more detail on the peat surveys.

Figure 7.4.5 provides a peat depth map of the Proposed Development interpolated from the Phase 1 and Phase 2 peat depth surveys, with probing locations superimposed. Interpolation of peat depths was undertaken in the ArcMap GIS environment using a natural neighbour approach. This approach was selected because it preserves recorded depths at each probe location, unlike some other approaches (e.g. kriging), is computationally simple, and minimises 'bullseye' effects. The approach was selected after comparison of outputs with three other methods (inverse distance weighted, kriging and TIN).

Figure 7.4.5 indicates that:

- Peat is widespread across the Proposed Development, peaking in depth along a northeast-southwest axis in a number of large pockets of very deep peat between the area north of the proposed met mast and east of Turbine 10.
- Depths decline with reducing elevation towards the southeast along the route of the proposed access track.
- Many of the larger lochans, despite being in low lying areas, are surrounded by shallower organic soils, rather than deeper peat.

Comparison of the peat depth model with the layout indicates that significant efforts have been made during layout design to site infrastructure out of the deepest peat areas and to route access tracks onto shallower peat. Typically, this process involved minimising the overlap of permanent excavation footprints with deeper deposits, mirroring hardstandings to further reduce overlap, and adjusting track alignments away from pockets of deep peat. Further details on the iterative site design adopted for An Carr Dubh (which took account of all constraints, not just peat) are provided in the Chapter 3 of the EIA Report.

3.6. Peatland Geomorphology

Both Google Earth™ and bing.com satellite imagery available as ArcGIS Basemap layers were initially reviewed to determine their suitability for use in mapping geomorphological features at the Site. However, at the time of project inception, these datasets showed poor contrast and resolution and were considered of insufficient quality to characterise the Site. Accordingly, 25 cm resolution orthorectified aerial imagery was purchased to enable reliable interpretation and mapping of peatland

features. The resulting geomorphological map, shown on Figure 7.4.4, was subsequently verified during a site walkover undertaken in July 2021 by a Chartered Geologist / peatland geomorphologist with over 25 years' experience of assessing peat landslides. Plates 3.2 and 3.3 show typical features identified during the walkovers.

Figure 7.4.4 shows the key features of the Site. The presence, characteristics and distribution of these features are helpful in understanding the hydrological function of a peatland, the balance of erosion and peat accumulation (or condition), and the sensitivity of a peatland to potential land-use changes.



Plate 3.2 a) bare peat in an actively eroding haggged area, b) recovered hagsgs with only bare sidewalls now visible

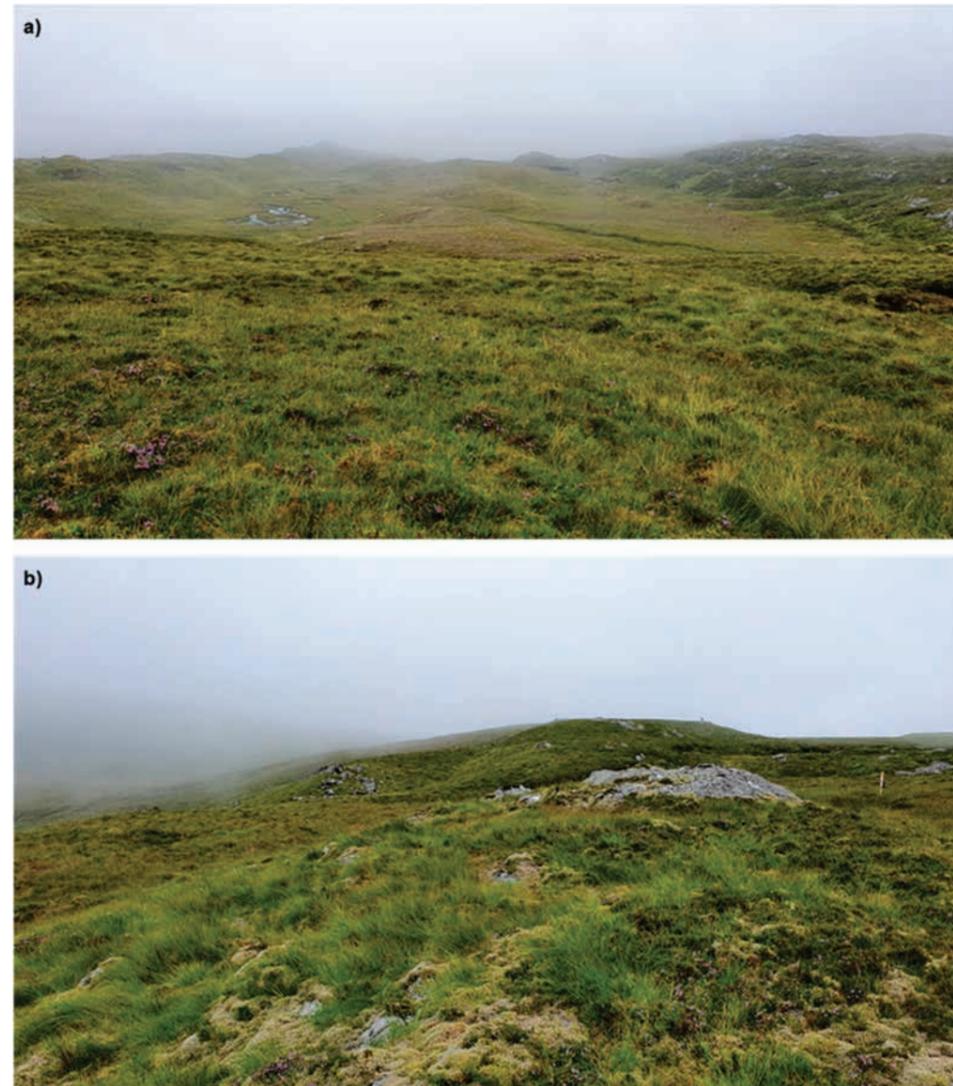


Plate 3.3 a) typical ridge and trough topography with blanket bog habitats, b) typical ridge top conditions with local rock outcrops

The Site is characterised by ridge and trough topography, with deeper peat tending to occur in troughs or on gently southeast facing slopes in the centre of the Site. Where peat is deepest, it is often eroded, with areas of bare and drying peat pans, hagged margins and isolated acrotelm-topped islands of intact peat. There are also many areas of apparently recovered hagged peat, where the lower ground between peat islands is now well vegetated. There was very limited evidence for instability on the Site, with only very minor gully head or gully sidewall collapses evident in one or two locations (and away from proposed infrastructure).

4. ASSESSMENT OF PEAT LANDSLIDE LIKELIHOOD

4.1. Introduction

This section provides details on the landslide susceptibility and limit equilibrium approaches to assessment of peat landslide likelihood used in this report. The assessment of likelihood is a key step in the calculation of risk, where risk is expressed as follows:

$$\text{Risk} = \text{Probability of a Peat Landslide} \times \text{Adverse Consequences}$$

The probability of a peat landslide is expressed in this report as peat landslide likelihood, and is considered below.

Due to the combination of moderate slopes and thinner peat at this site, the most likely mode of failure is peat slides, and this is the failure mechanism considered in this report. This is in keeping with the most likely mode of failure for the peat depths and slope angles present at the Site (see Plate 2.2 and Figures 7.3.2 and 7.3.5).

4.2. Limit Equilibrium Approach

4.2.1. Overview

Stability analysis has been undertaken using the infinite slope model to determine the Factor of Safety (FoS) for a series of 25 m x 25 m grid cells within the Proposed Development boundary. This is the most frequently cited approach to quantitatively assessing the stability of peat slopes (e.g. Scottish Government, 2017; Boylan et al, 2008; Evans and Warburton, 2007; Dykes and Warburton, 2007; Creighton, 2006; Warburton et al, 2003; Carling, 1986). The approach assumes that failure occurs by shallow translational landsliding, which is the mechanism usually interpreted for peat slides. Due to the relative length of the slope and depth to the failure surface, end effects are considered negligible and the safety of the slope against sliding may be determined from analysis of a 'slice' of the material within the slope.

The stability of a peat slope is assessed by calculating a Factor of Safety, F, which is the ratio of the sum of resisting forces (shear strength) and the sum of driving forces (shear stress) (Scottish Government, 2017):

$$F = \frac{c' + (\gamma - h\gamma_w)z \cos^2 \beta \tan \phi'}{\gamma z \sin \beta \cos \beta}$$

In this formula c' is the effective cohesion (kPa), γ is the bulk unit weight of saturated peat (kN/m^3), γ_w is the unit weight of water (kN/m^3), z is the vertical peat depth (m), h is the height of the water table as a proportion of the peat depth, β is the angle of the substrate interface ($^\circ$) and ϕ' is the angle of internal friction of the peat ($^\circ$). This form of the infinite slope equation uses effective stress parameters, and assumes that there are no excess pore pressures, i.e. that the soil is in its natural, unloaded condition. The choice of water table height reflects the full saturation of the soils that would be expected under the most likely trigger conditions, i.e. heavy rain.

Where the driving forces exceed the shear strength (i.e. where the bottom half of the equation is larger than the top), F is < 1 , indicating instability. A factor of safety between 1 and 1.4 is normally taken in engineering to indicate marginal stability (providing an allowance for variability in the strength

of the soil, depth to failure, etc). Slopes with a factor of safety greater than 1.4 are generally considered to be stable.

There are numerous uncertainties involved in applying geotechnical approaches to peat, not least because of its high water content, compressibility and organic composition (Hobbs, 1986; Boylan and Long, 2014). Peat comprises organic matter in various states of decomposition with both pore water and water within plant constituents, and the frictional particle-to-particle contacts that are modelled in standard geotechnical approaches are different in peats. There is also a tensile strength component to peat which is assumed to be dominant in the acrotelm, declining with increasing decomposition and depth. As a result, analysis utilising geotechnical approaches is often primarily of value in showing relative stability across a site given credible and representative input parameters rather than in providing an absolute estimate of stability. Representative data inputs have been derived from published literature for drained analyses considering natural site conditions.

4.2.2. Data Inputs

Stability analysis was undertaken in ArcMap GIS software. A 25 m x 25 m grid was superimposed on the full site extent and key input parameters derived for each grid cell. In total, c. 13,640 grid cells were analysed. A 25 m x 25 m cell size was chosen as it is sufficiently small to define a credible landslide size and avoid 'smoothing' of important topographic irregularities.

Table 4.1 shows the input parameters and assumptions for the baseline stability analysis. The shear strength parameters c' and ϕ' are usually derived in the laboratory using undisturbed samples of peat collected in the field and therefore site specific values are often not available ahead of detailed site investigation for a development. Therefore, for this assessment, a literature search has been undertaken to identify a range of credible but conservative values for c' and ϕ' quoted in fibrous and humified peats. FoS analysis was undertaken with conservative ϕ' of 20° and values of 2 kPa and 5 kPa for c' . These values fall at the low end of a large range of relatively low values (when compared to other soils).

4.2.3. Results

The outputs of the drained analysis (effective stress) are shown for both parameter combinations in Figure 7.4.6. The more conservative combination (minimum c' and ϕ' , inset panel) suggests that a significant proportion of the site is either unstable ($F < 1$) or of marginal stability ($F < 1.4$) which is not consistent with site observations nor with the stability of peat in general – peat landslides are very rare occurrences given the wide distribution of peat soils in England, Scotland and Wales. The less conservative combination (main panel) gives more credible results, with areas of local marginal stability ($F < 1.4$) on the steeper southeast facing slopes, particularly on the ridge margins where there is still some appreciable peat thickness but slopes are steeper.

Parameter	Values	Rationale	Source
Effective cohesion (c')	2, 5	Credible conservative cohesion values for humified peat based on literature review	5, basal peat (Warburton et al., 2003) 8.74, fibrous peat (Carling, 1986) 7 - 12, H8 peat (Huat et al, 2014) 5.5 - 6.1, type not stated (Long, 2005) 3, 4, type not stated (Long, 2005) 4, type not stated (Dykes and Kirk, 2001)
Bulk unit weight (γ)	10.5	Credible mid-range value for humified catotelmic peat	10.8, catotelm peat (Mills, 2002) 10.1, Irish bog peat (Boylan et al 2008)

Parameter	Values	Rationale	Source
Effective angle of internal friction (ϕ')	20, 30	Credible conservative friction angles for humified peat based on literature review (only 20° used in analysis)	40 - 65, fibrous peat (Huat et al, 2014) 50 - 60, amorphous peat (Huat et al, 2014) 36.6 - 43.5, type not stated (Long, 2005) 31 - 55, Irish bog peat (Hebib, 2001) 34 - 48, fibrous sedge peat (Farrell & Hebib, 1998) 32 - 58, type not stated (Long, 2005) 23, basal peat (Warburton et al, 2003) 21, fibrous peat (Carling, 1986)
Slope angle from horizontal (β)	Various	Mean slope angle per 25 m x 25 m grid cell	5 m digital terrain model of site
Peat depth (z)	Various	Mean peat depth per 25 m x 25 m grid cell	Interpolated peat depth model of site
Height of water table as a proportion of peat depth (h)	1	Assumes peat mass is fully saturated (normal conditions during intense rainfall events or snowmelt, which are the most likely natural hydrological conditions at failure)	

Table 4.1 Geotechnical parameters for drained infinite slope analysis

4.3. Landslide Susceptibility Approach

4.3.1. Overview

The landslide susceptibility approach is based on the layering of contributory factors to produce unique 'slope facets' that define areas of similar susceptibility to failure. These slope facets vary in size and are different to the regular grid used for the FoS approach. The number and size of slope facets varies from one part of the site to another according to the complexity of ground conditions. In total, c. 7,000 facets were considered in the analysis, with an average area of c. 1,200 m² (or an average footprint of c. 35 m x 35 m, consistent with smaller to medium scale peaty soil or peat slides reported in the published literature.

Eight contributory factors are considered in the analysis: slope angle (S), peat depth (P), substrate geology (G), peat geomorphology (M), drainage (D), slope curvature (C), forestry (F), and land use (L). For each factor, a series of numerical scores between 0 and 3 are assigned to factor 'classes', the significance of which is tabulated for each factor. The higher a score, the greater the contribution of that factor to instability for any particular slope facet. Scores of 0 imply neutral / negligible influence on instability.

Factor scores are summed for each slope facet to produce a peat landslide likelihood score (S_{PL}), the maximum being 24 (8 factors, each with a maximum score of 3).

$$S_{PL} = S_S + S_P + S_G + S_M + S_D + S_C + S_F + S_L$$

In practice, a maximum score is unlikely, as the chance of all contributory factors having their highest scores in one location is very small. The following sections describe the contributory factors, scores and justification for the Proposed Development.

4.3.2. Slope Angle (S)

Table 4.2 shows the slope ranges, their association with instability and related scores for the slope angle contributory factor. Slope angles were derived from the 5 m digital terrain model shown on Figures 7.4.1 and 7.4.2 and scores assigned based on reported slope angles associated with peat

landslides rather than a simplistic assumption that 'the steeper a slope, the more likely it is to fail' (e.g. Plate 2.2). A differentiation in scores is applied for peat slides and bog bursts reflecting the shallower slopes on which the latter are most frequently observed.

Note that the slope model is a TIN (interpolated from irregularly spaced measures of elevation) and these types of slope model tend to simplify slopes into triangular surfaces – this can have the effect of steepening or shallowing slopes relative to their actual gradients.

Slope range (°)	Association with instability	Peat slide
≤2.5	Slope angle ranges for peat slides are based on lower and upper limiting angles for observations of occurrence (see Plate 2.2 and increase with increasing slope angle until the upper limiting angle e.g. peat slides are not observed on slopes <2.5°	0
2.5 - 5.0		1
5.0 – 7.5		3
7.5 - 10.0		3
10 – 15.0		3
>15.0		3

Table 4.2 Slope classes, association with instability and scores

Figure 7.4.7 shows the distribution of slope angle scores across the Site. Other than in the gently undulating central plateau (where peat depths are greatest), much of the Site receives the maximum score for the slope factor reflecting the relatively wide range of slopes over which peat slides have been recorded.

4.3.3. Peat Depth (P)

Table 4.3 shows the peat depths, their association with instability and related scores for the peat depth contributory factor. Peat depths were derived from the peat depth model shown on Figure 7.4.5 and reflect the peat depth ranges most frequently associated with peat landslides (see Plate 2.2).

Peat depth range (m)	Association with instability	Peat slide
>1.5	Bog bursts are the dominant failure mechanism in this depth range where basal peat is more likely to be amorphous	1
0.5 - 1.5	Peat slides are the dominant failure mechanism in this depth range where basal peat is less likely to be amorphous	3
<0.5	Organic soil rather than peat, failures would be peaty-debris slides rather than peat slides or bog bursts and are outside the scope	0

Table 4.3 Peat depth classes, association with instability and scores

The distribution of peat depth scores is shown on Figure 7.4.7. It is typically the areas of moderate slope that receive the highest peat depth scores, where peat is of intermediate thickness.

4.3.4. Substrate Geology (G)

Table 4.4 shows substrate type, association with instability and related scores for the substrate geology contributory factor. The shear surface or failure zone of reported peat failures typically overlies an impervious clay or mineral (bedrock) base giving rise to impeded drainage. This, in part, is responsible for the presence of peat, but also precludes free drainage of water from the base of the peat mass, particularly under extreme conditions (such as after heavy rainfall, or snowmelt).

Peat failures are frequently cited in association with glacial till deposits in which an iron pan is observed in the upper few centimetres (Dykes and Warburton, 2007). They have also been observed over glacial till without an obvious iron pan, or over impermeable bedrock. They are rarely cited over permeable bedrock, probably due to the reduced likelihood of peat formation.

Substrate Geology	Association with instability	Peat slide
Cohesive (clay) or iron pan	Failures are often associated with sticky clay substrates and/or iron pans	3
Unknown / gravelly clay	Failures are occasionally associated with clay with a granular component	2
Granular or bedrock	Failures are less frequently associated with bedrock or granular (silt / sand / gravel) substrates	1

Table 4.4 Substrate geology classes, association with instability and scores

Coring undertaken at turbine locations (and documented in EIAR Appendix 7.2) indicates a possible band of moderately clayey / gravelly clay substrate in the centre of the Site. In this area, an intermediate score of 2 is assigned, while elsewhere with bedrock close to the surface, a score of 1 is applied. Figure 7.4.7 shows the distribution of scores.

4.3.5. Peat Geomorphology (M)

Table 4.5 shows the geomorphological features typical of peatland environments, their association with instability and related scores. Being an open moorland site (rather than afforested), there is a strong degree of confidence in the identification and mapping of these features, where present.

Geomorphology	Association with instability	Peat slide
Incipient instability (cracks, ridges, bulging)	Failures are likely to occur where pre-failure indicators are present	3
Planar with pipes	Failures generally occur on planar slopes, and are often reported in areas of piping	3
Planar with pools / quaking bog	Bog bursts are more likely in areas of perched water (pools) or subsurface water bodies (quaking bog)	2
Flush / Sphagnum lawn / inter-ridge trough	Peat slides are often reported in association with areas of flushed peat or diffuse drainage	3
Planar (no other features)	Failures generally occur on planar slopes rather than dissected or undulating slopes	2
Peat between rock outcrops	Failures are rarely reported in areas of peat with frequent rock outcrops	1
Slightly eroded / dendritic drainage / minor gullies	Failures are rarely reported in areas with gullying or bare peat	1
Ridged rock outcrop / non-peat terrain	Failures do not occur where peat is absent	0
Heavily eroded /hagged peat / extensive gullies / bare peat	Failures are not reported in areas that are heavily eroded or bare	0
Afforested / deforested peatland / made ground	Considered within Forestry (F) or Land Use (L), see below	0

Table 4.5 Peat geomorphology classes, association with instability and scores

Figure 7.4.7 shows the geomorphological classes from Figure 7.4.4 re-coloured to correspond with Table 4.5. Much of the Site comprises planar slopes (with moderate scores) with the exception of ridged rock outcrops (which have low scores) and inter-ridge troughs with flushed floors (which have high scores). No significant instability features identified.

4.3.6. Artificial Drainage (D)

Table 4.6 shows artificial drainage feature classes, their association with instability and related scores. Transverse (or contour aligned) / oblique artificial drainage lines may reduce peat stability by creating lines of weakness in the peat slope and encouraging the formation of peat pipes. A number of peat failures have been identified in published literature which have failed over moorland grips (Warburton et al, 2004). The influence of changes in hydrology becomes more pronounced the more transverse the orientation of the drainage lines relative to the overall slope.

Drainage Feature	Association with instability	Peat slide
Drains aligned along contours (<15 °)	Drains aligned to contour create lines of weakness in slopes	3
Drains oblique (15-60°) to contour	Most reports of peat slides and bog bursts in association with drainage occurs where drains are oblique to slope	2
Drains aligned downslope (<30° to slope)	Failures are rarely associated with artificial drains parallel to slope or adjacent to natural drainage lines	1
No / minimal artificial drainage	No influence on stability	0

Table 4.6 Drainage feature classes, association with instability and scores

The effect of drainage lines is captured through the use of a 30 m buffer on each artificial drainage line (producing a 60 m wide zone of influence) present within the peat soils at the Site. Each buffer is assigned a drainage feature class based on comparison of the drainage axis with elevation contours (transverse, oblique or aligned, as shown in Table 4.6). Scored buffers are shown on Figure 7.4.7.

4.3.7. Slope Curvature (C)

Table 4.7 shows slope (profile) curvature classes, association with instability and related scores. Convex and concave slopes (i.e. positions in a slope profile where slope gradient changes by a few degrees) have frequently been reported as the initiation points of peat landslides by a number of authors. The geomechanical reason for this is that convexities are often associated with thinning of peat, such that thicker peat upslope applies stresses to thinner 'retaining' peat downslope. Conversely, buckling and tearing of peat may trigger failure at concavities (e.g. Dykes & Warburton, 2007; Boylan and Long, 2011). However, review of reported peat landslide locations against Google Earth elevation data indicates that the majority of peat slides occur on rectilinear (straight) slopes and that the reporting of convexity as a key driver may be misleading. Accordingly, rectilinear slopes are assigned the highest score.

Profile Curvature	Association with instability	Peat slide
Rectilinear Slope	Peat slides are most frequently reported on rectilinear slopes, while bog bursts are often reported on rectilinear slopes	3

Profile Curvature	Association with instability	Peat slide
Convex Slope	Peat slides are often reported on or above convex slopes while bog bursts are most frequently associated with convex slopes	2
Concave Slope	Peat failures are occasionally reported in association with concave slopes	1
Compartmentalised	Peat failures are very rarely reported on undulating slopes with short slope lengths	0

Table 4.7 Slope curvature classes, association with instability and scores

The 5 m digital terrain model and OS contours were used to identify areas of noticeable slope convexity and concavity across the Site. Axes of convexity and concavity (running along the contour) were assigned a 50 m buffer to produce 100 m (upslope to downslope) convexity/concavity zones and these were assigned scores in accordance with Table 4.7 above. Due to the high degree of slope compartmentalisation (with short slope lengths), an additional class was used to reflect the lack of downslope continuity of slope (and therefore limited contiguous lengths of peat of consistent depth). This aligns with the general lack of reported peat slides in areas with extensive rocky outcrops or strong geological texture.

4.3.8. Forestry (F)

Table 4.8 shows forestry classes, their association with instability and related scores. A report by Lindsay and Bragg (2004) on Derrybrien suggested that row alignments, desiccation cracking and loading (by trees) could all influence peat stability.

Forestry Class	Association with instability	Peat slide
Deforested, rows oblique to slope	Deforested peat is less stable than afforested peat, and inter ridge cracks oblique to slope may be lines of weakness	3
Deforested, rows aligned to slope	Deforested peat is less stable than afforested peat, but slope aligned inter ridge cracks have less impact	2
Afforested, rows oblique to slope	Afforested peat is more stable than deforested peat, but inter ridge cracks oblique to slope may be lines of weakness	2
Afforested, rows aligned to slope	Afforested peat is more stable than deforested peat, but potentially less stable than unforested (never planted) peat	1
Windblown	Windblown trees have full disruption to the underlying peat and residual hydrology due to root plate disturbance	0
Not afforested	No influence on stability	0

Table 4.8 Forestry classes, association with instability and scores

Only a small part of the Site is afforested in an area where existing track will be upgraded, and therefore the vast majority of the Site receives a zero score for this factor (see Figure 7.4.7).

4.3.9. Land use (L)

Table 4.9 shows land use classes, association with instability and related scores. A variety of land uses have been associated with peat failures (see 2.2.1). While it is hypothesised that burning may cause desiccation cracking in peat and facilitate water flows to basal peat (and potential shear surfaces), there is little evidence directly relating burnt ground to peat landslide events.

Land Use	Association with instability	Peat slide
Machine cutting	Machine cutting may compartmentalise slopes, but has been reported primarily in association with peat slides	3
Quarrying	Quarrying may remove slope support from upslope materials, and has been observed with spreading failures (bog bursts)	2
Hand cutting (turbary)	Hand cutting may remove slope support from upslope materials, and has been reported with raised bog failures	1
Burning (deep cracking to substrate)	Failures are rarely associated with burning, but deep desiccation cracking will have the most severe effects	2
Burning (shallow cracking)	Failures are rarely associated with burning, shallow desiccation cracking will have very limited effects	1
Grazing	Failures have not been associated with grazing, no influence on stability	0

Table 4.9 Land use classes, association with instability and scores

Grazing is the primary land use on site and is not associated with peat instability. Scores are shown on Figure 7.4.7.

4.3.10. Generation of Slope Facets

The eight contributory factor layers shown on Figure 7.4.7 were combined in ArcMap to produce approximately 7,000 slope facets. Scores for each facet were then summed to produce a peat landslide likelihood score. These likelihood scores were then converted into descriptive 'likelihood classes' from 'Very Low' to 'Very High' with a corresponding numerical range of 1 to 5 (in a similar format to the Scottish Government BPG).

Summed Score from Contributory Factors	Typical site conditions associated with score	Likelihood (Qualitative)	Landslide Likelihood Score
≤ 7	Unmodified peat with no more than low weightings for peat depth, slope angle, underlying geology and peat morphology	Very Low	1
8 - 12	Unmodified or modified peat with no more than moderate or some high scores for peat depth, slope angle, underlying geology and peat morphology	Low	2
13 - 17	Unmodified or modified peat with high scores for peat depth and slope angle and / or high scores for at least three other contributory factors	Moderate	3
18 - 21	Modified peat with high scores for peat depth and slope angle and several other contributory factors	High	4
> 21	Modified peat with high scores for most contributory factors (unusual except in areas with evidence of incipient instability)	Very High	5

Table 4.10 Likelihood classes derived from the landslide susceptibility approach

Table 4.10 describes the basis for the likelihood classes. A judgement was made that for a facet to have a moderate or higher likelihood of a peat landslide, a likelihood score would be required exceeding both the worst case peat depth and slope angle scores summed (3 in each case, i.e. 3 x 2 classes) alongside three intermediate scores (of 2, i.e. 2 x 3 classes) for other contributory factors. This means that any likelihood score of 13 or greater would be equivalent to at least a moderate likelihood of a peat landslide. Given that the maximum score attainable is 24, this seems reasonable.

4.3.11. Results

Figure 7.4.8 shows the outputs of the landslide susceptibility approach. The results indicate that the majority of the Site has a 'Low' or 'Very Low' likelihood of instability, with isolated areas of 'Moderate' likelihood in the deeper peat areas in the main turbine area. Areas of 'Moderate' likelihood are typically located on moderate slopes with moderate peat depths and where drains are present. There are no areas identified with 'High' or 'Very High' landslide likelihood. When compared with the stability analysis approach, the outputs of this approach indicate slightly more of the Site to be at lower stability under natural conditions.

4.3.12. Combined Landslide Likelihood

Figure 7.4.9 shows in purple any proposed areas of infrastructure of greater than 25 m in length intersecting with areas of moderate or higher landslide likelihood (from the contributory factor approach) or Factor of Safety of 1.4 or less (from the limit equilibrium approach). A 25 m overlap has been selected as this is considered the minimum size of a potentially environmentally significant landslide. For there to be a "Medium" or "High" risk (Scottish Government, 2017), likelihoods must be "Moderate" or higher (see Plate 4.1 below) and hence this provides a screening basis for the likelihood results. Only 1 infrastructure location meets these criteria, and this location is considered in Section 5. There are small overlaps of <20 m in one or two locations elsewhere, however these are interpreted to be of insufficient size to generate a peat slide of the scale and morphology addressed by the Best Practice Guidance.

		Adverse Consequence (scores bracketed)				
		Very High (5)	High (4)	Moderate (3)	Low (2)	Very Low (1)
Peat landslide likelihood (scores bracketed)	Very High (5)	High	High	Medium	Low	Low
	High (4)	High	Medium	Medium	Low	Negligible
	Moderate (3)	Medium	Medium	Low	Low	Negligible
	Low (2)	Low	Low	Low	Negligible	Negligible
	Very Low (1)	Low	Negligible	Negligible	Negligible	Negligible

Score	Risk Level	Action suggested for each zone
17 - 25	High	Avoid project development at these locations
11 - 16	Medium	Project should not proceed in MEDIUM areas unless risk can be avoided or mitigated at these locations, without significant environmental impact, in order to reduce risk ranking to LOW or NEGLIGIBLE.
5 - 10	Low	Project may proceed pending further post-consent investigation in LOW areas to refine risk level and/or mitigate any residual hazards through micro-siting or specific design measures
1 - 4	Negligible	Project should proceed with good practice monitoring and mitigation of ground instability / landslide hazards at these locations as appropriate

Plate 4.1 Top: risk ranking as a product of likelihood and consequence; Bottom: suggested action given each level of calculated risk

5. ASSESSMENT OF CONSEQUENCE AND RISK

5.1. Introduction

To calculate risks, the potential consequences of a peat landslide must be determined. This requires identification of receptors and an assessment of the consequences for these receptors should a peat landslide occur. This section describes the consequence assessment and then provides risk results based on the product of likelihood and consequence.

5.2. Receptors

Peat uplands are typically host to the following receptors: watercourses and associated water supplies (both private and public), terrestrial habitats (e.g. groundwater dependent terrestrial ecosystems or Ground Water Dependant Terrestrial Ecosystems [GWDTEs]) and infrastructure, both those that are related to the wind farm and other infrastructure, e.g. roads and power lines. These are considered for the Proposed Development below.

5.2.1. Watercourses

The Proposed Development site is drained by a number of watercourses (see Section 3.3), however, the main rivers are of Moderate ecological status and are not designated. The primary receptor in the north of the Site is the Allt Blarghour hydroelectric scheme intake, however, the one identified source zone (Figure 7.4.9) is not within this catchment, and lies in the Erallich Water catchment. Given the Moderate status of this watercourse and given that the impact zone lies on a minor tributary of the Erallich Water, a consequence score of 2 is assigned for short term increases in acidity and turbidity.

5.2.2. Habitats

While blanket bog habitats are valuable, they generally recover from instability events through revegetation over a matter of years to decades. The habitats downslope of the source zone are indicated to be M15/M23/U20, i.e. wet heath / acid grassland over relatively shallow peat on moderate slopes with a High potential of GWDTE, and therefore a consequence score of 3 is assigned for these terrestrial habitats (See Table 5.1).

Receptor and type	Consequence	Score	Justification for Consequence Score
Watercourses (aquatic habitats)	Short term increase in turbidity and acidification, potential fish kill	2	Undesignated watercourse, no sensitive species noted
Terrestrial habitats	Short to medium term loss of vegetation cover, disruption of peat hydrology, carbon release	3	Best habitats generally of moderate quality though High GWDTE noted, long term effects unlikely following revegetation
Infrastructure (culvert)	Short term temporary blockage of water crossing culvert that may require remedial work	2	Minimal likelihood of impact on site personnel, minor remedial works required that would not likely affect construction programme

Table 5.1 Receptors considered in the consequence analysis

5.2.3. Infrastructure

The Proposed Development site is relatively isolated, with non-wind farm infrastructure limited to the Allt Blarghour and Kames hydroelectrical schemes and commercial forestry tracks away from the peat areas. None of the proposed wind farm infrastructure is located downslope of the source zone other than the water crossing adjacent to the forest margin (approximately 0.8 km downstream). While short term blockage of the water crossing culvert may occur in the event of a landslide, it is considered very unlikely that any impact would affect the integrity of the track or personnel using the water crossing, with good line of sight upvalley towards the source zone. A consequence score of 2 is assigned for remedial works at the culvert that may be required in the event of a landslide occurring.

5.3. Consequences

5.3.1. Overview

A consequence assessment has been undertaken by determining the potential for a landslide sourced at the infrastructure location with a Moderate natural likelihood of peat instability to impact the receptors identified above. As an example, if a turbine is located in a Moderate (likelihood score of 3) area of open slope and is located 50 m from a watercourse (with a consequence score of 5), it is probable that a landslide triggered during construction would reach that watercourse. The calculated risk would be a product of the likelihood and consequence scores (likelihood: 3 x consequence: 5 = risk: 15, see Plate 4.1) and be equivalent to a “Medium” risk.

To determine the likelihood of impact on watercourses and infrastructure, ‘runout pathways’ have been defined that show the estimated maximum footprint of the landslide. Runout pathways are divided in a downslope direction into 50 m, 100 m, 250 m and 500 m zones on the basis of typical runout distances detailed in Mills (2002). The likelihood of runout passing from one runout zone to the next (e.g. from the 50 m zone into the 100 m zone) is based on the proportion of the published peat landslide population that reaches each runout distance shown on Plate 5.1 (0-50 m: 100%, 50-100 m: 87%, 100-250 m: 56%, 250-500 m: 44%). The first 50 m includes the landslide source area.

Figure 7.4.9 shows in purple all infrastructure locations that overlap with moderate likelihoods, based on the combined landslide likelihood scores described in Section 4. Only one location overlaps with moderate likelihoods, and the lower left zoom inset on Figure 7.4.9 shows this location (which is on the main access track).

5.3.2. Local limits on runout (watercourses)

Where runout pathways terminate at “blue line” watercourses (those shown on 1:10,000 scale Ordnance Survey maps), an assessment has been made of the ability to convey landslide material along the watercourse. This reflects the significant variability in dimensions of “blue line” watercourses on the ground such that some may be several metres wide and metres deep (and therefore able to transmit materials kilometres downstream) where others may be <0.5 m in width, highly sinuous and sometimes discontinuous (disappearing under the peat surface) and therefore unable to convey landslide material. The minor tributary into which runout may occur is c. 1 m in width in the valley floor and narrower immediately adjacent to the source zone, therefore it is likely to have limited ability to convey material downslope, other than when in spate, however these conditions are the most likely to be associated with landslide occurrence, and some downslope conveyance to the water crossing culvert is still considered a possibility.

5.3.3. Local limits on runout (slope curvature)

Plate 5.1 shows runout distances based on published literature. Typically, runout distances would be expected to be less where slope angles decline with distance from the source zone (i.e. on concave slopes) whereas the full runout lengths shown on Plate 5.1 may be achievable on steepening (convex) slopes or rectilinear slopes. The slope below the source zone down to the minor watercourse is relatively continuous and no restrictions on runout from topography are expected.

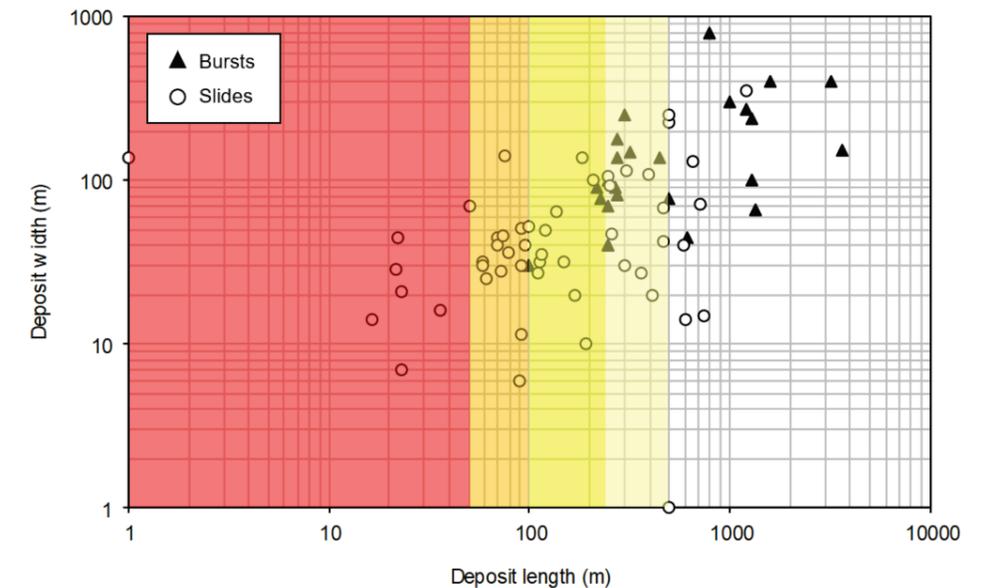


Plate 5.1 Runout distances for published peat landslides (after Mills, 2002), colours on the plot correspond to runout pathway zones on the left inset zoom Figure 7.4.9

5.3.4. Local limits on runout (peat thickness in source zone)

Landslide runout may be “supply-limited” by the availability of peat material generated in the failure or source zone. Typically, mobilised material thins with increasing distance from the source zone as rafts of landslide material break down into blocks, and blocks become abraded and roll, breaking down further into a blocky slurry (Plate 5.1).

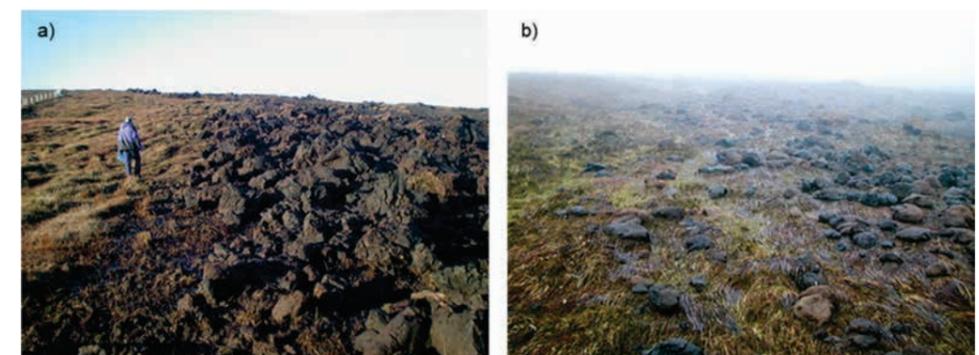


Plate 5.1 Examples of landslide runout (Dooncarton, Co. Mayo): a) blocky debris mid-slope, b) abraded and rolled blocks in lower slope

Following identification of runout zones, additional analysis has been undertaken to approximate this effect. The analysis assumes a source volume equivalent to the source footprint (0 m - 50 m zone) multiplied by the average peat depth in this source zone (from the peat depth model). This volume is then distributed over the full runout pathway (i.e. mobilised volume / runout area) to generate an average thickness of deposit. As the runout length and area increases, the volume thins, in keeping with observed peat landslide deposits. Where deposits fall below 0.2 m in thickness, it is assumed that runout will stall due to the roughness of surface vegetation relative to the thickness of landslide material. If the thickness is calculated to be 0.2 m or less in the zone adjoining a watercourse, then it is judged that there will be no significant impact on that watercourse (even if a landslide occurs).

5.3.5. Results of runout analysis

Runout from the one source location identified would enter the adjacent minor watercourse almost immediately at a thickness of c. 0.8 m (the thickness of the source zone) as well as running downslope parallel to the watercourse and joining the larger tributary in the valley floor below. Based on reduction in deposit thickness with distance, the thickness when entering the valley floor would still be c. 0.5 m. It is likely that this material would mobilise some distance downstream, certainly to the next watercourse crossing, however it is considered unlikely that it would be conveyed a significant distance into the forestry along the Allt Bail' a' Ghobainn due to the relatively small size of the potential failure and the relatively confined and sinuous nature of the watercourse.

5.4. Calculated Risk

The risk level associated with the source zone has been calculated as a product of likelihood and consequence and is shown as the right of two zoomed insets on Figure 7.4.9 for the runout pathway. The runout zones within the runout pathway are colour coded to match the risk rankings shown on **Error! Reference source not found.** For each zone, the score for the most sensitive environmental receptor has been chosen for the risk calculation (i.e. a conservative approach). Both the watercourse receptor and habitat receptor result in risks calculated to be "Low" within the runout pathway. There are no areas with "Medium" or "High" calculated risks.

Based on the calculated risks shown on Figure 7.4.9, site-wide good practice measures should be sufficient to manage and mitigate any construction induced instability risks. This is considered in the next section.

5.5. Restoration Activities

As part of the peat management proposals for the Proposed Development, a number of hagged areas have been recommended for restoration using peat excavated primarily from turbine foundations and hardstandings. As part of the assessment for this restoration work, all Moderate likelihood and areas with Factors of Safety < 1.4 were compared with potential restoration areas, and if present, those hagged areas were excluded from the restoration proposals. Further information on managing the relocated materials is provided in Appendix 7.3 of the EIAR.

6. RISK MITIGATION

6.1. Overview

A number of mitigation opportunities exist to further reduce the risk levels identified at the Proposed Development site. These range from infrastructure specific measures (which may act to reduce peat landslide likelihood, and, in turn, risk) to general good practice that should be applied across the Site to engender awareness of peat instability and enable early identification of potential displacement and opportunities for mitigation.

Risks may be mitigated by:

- i. Post-consent site specific review of the ground conditions contributing to Moderate likelihoods which may result in a reduced likelihood, and in turn, further reduction in risk; examples include tension cracks along the peat escarpment and artificial drains aligned oblique to contour.
- ii. Precautionary construction measures – including use of monitoring, good practice and a geotechnical risk register relevant to all locations.

Based on the analysis presented in this report, risks are calculated to be "Low" to "Negligible" for the Site, and site-specific mitigation is not required to reduce risks pre-consent. Sections 6.2 to 6.4 provide information on good practice pre-construction, during construction and post-construction (i.e. during operation).

6.2. Good Practice Prior to Construction

Site safety is critical during construction, and it is strongly recommended that detailed intrusive site investigation and laboratory analysis are undertaken ahead of the construction period in order to characterise the strength of the peat soils in the areas in which excavations are proposed, particularly where these fall in areas of LOW or greater risk. These investigations should be sufficient to:

1. Determine the strength of free-standing bare peat excavations.
2. Determine the strength of loaded peat (where excavators and plant are required to operate on floating hardstandings or track, or where operating directly on the bog surface).
3. Identify sub-surface water-filled voids or natural pipes delivering water to the excavation zone, e.g. through the use of ground penetrating radar or careful pre-excavation site observations.

A comprehensive Geotechnical Risk Register should be prepared post-consent but pre-construction detailing sequence of working for excavations, measures to minimise peat slippage, design of retaining structures for the duration of open hole works, monitoring requirements in and around the excavation and remedial measures in the event of unanticipated ground movement. The risk register should be considered a live document and updated with site experience as infrastructure is constructed. Ideally, a contractor with experience of working in deep peat should be engaged to undertake the works.

6.3. Good Practice During Construction

The following good practice should be undertaken during construction:

For excavations:

- Use of appropriate supporting structures around peat excavations (e.g. for turbines, crane pads and compounds) to prevent collapse and the development of tension cracks.

- Avoid cutting trenches or aligning excavations across slopes (which may act as incipient back scars for peat failures) unless appropriate mitigation has been put in place.
- Implement methods of working that minimise the cutting of the toes of slope, e.g. working up-to-downslope during excavation works.
- Monitor the ground upslope of excavation works for creep, heave, displacement, tension cracks, subsidence or changes in surface water content.
- Monitor cut faces for changes in water discharge, particularly at the peat-substrate contact.
- Minimise the effects of construction on natural drainage by ensuring that natural drainage pathways are maintained or diverted such alteration of the hydrological regime of the Site is minimised or avoided; drainage plans should avoid creating drainage/infiltration areas or settlement ponds towards the tops of slopes (where they may act to both load the slope and elevate pore pressures).

For cut tracks:

- Maintain drainage pathways through tracks to avoid ponding of water upslope.
- Monitor the top line of excavated peat deposits for deformation post-excavation.
- Monitor the effectiveness of cross-track drainage to ensure water remains free-flowing and that no blockages have occurred.

For floating tracks:

- Allow peat to undergo primary consolidation by adopting rates of road construction appropriate to weather conditions.
- Identify 'stop' rules, i.e. weather dependent criteria for cessation of track construction based on local meteorological data.
- Run vehicles at 50% load capacity until the tracks have entered the second compression phase.
- Prior to construction, setting out the centreline of the proposed track to identify any ground instability concerns or particularly wet zones.

For storage of peat and for restoration activities:

- Ensure stored peat is not located upslope of working areas or adjacent to drains or watercourses.
- Avoid temporary storage of peat on slope gradients >3° where possible, and preferably store on ground with neutral slopes and natural downslope barriers to peat movement.
- For permanent restoration areas, undertake pre-construction UAV or topographic surveys to determine i) gradients of eroded floors of hagged areas (in order to inform/refine infill depths), and ii) position and integrity of intact peat hags into which berms and retaining structures may be keyed.
- Undertake regular monitoring of emplaced peat in restoration areas to identify evidence of creep or pressure on retaining structures (dams and berms)
- Monitor effects of wetting / re-wetting stored peat on surrounding peat areas, and prevent water build up on the upslope side of peat mounds.

- Maximise the interval between material deliveries over newly constructed tracks that are still observed to be within the primary consolidation phase.

In addition to these control measures, the following good practice should be followed:

- The geotechnical risk register prepared prior to construction should be updated with site experience as infrastructure is constructed.
- Full site walkovers should be undertaken at scheduled intervals to be agreed with the Local Authority to identify any unusual or unexpected changes to ground conditions (which may be associated with construction or which may occur independently of construction).
- All construction activities and operational decisions that involve disturbance to peat deposits should be overseen by an appropriately qualified geotechnical engineer with experience of construction on peat sites.
- Awareness of peat instability and pre-failure indicators should be incorporated in site induction and training to enable all site personnel to recognise ground disturbances and features indicative of incipient instability.
- A weather policy should be agreed and implemented during works, e.g. identifying 'stop' rules (i.e. weather dependent criteria) for cessation of track construction or trafficking.
- Monitoring checklists should be prepared with respect to peat instability addressing all construction activities proposed for the Site.

It is considered that taken together, these mitigation measures should be sufficient to reduce risks to construction personnel to Negligible by reducing consequences to minor injury or programme delay (i.e. Moderate consequences) with a Very Low likelihood of occurrence.

6.4. Good Practice Post-Construction

Following cessation of construction activities, monitoring of key infrastructure locations should continue by full site walkover to look for signs of unexpected ground disturbance, including:

- Ponding on the upslope side of infrastructure sites and on the upslope side of access tracks.
- Changes in the character of peat drainage within a 50 m buffer strip of tracks and infrastructure (e.g. upwelling within the peat surface upslope of tracks, sudden changes in drainage behaviour downslope of tracks).
- Blockage or underperformance of the installed site drainage system.
- Slippage or creep of stored peat deposits.
- Development of tension cracks, compression features, bulging or quaking bog anywhere in a 50 m corridor surrounding the site of any construction activities or site works.

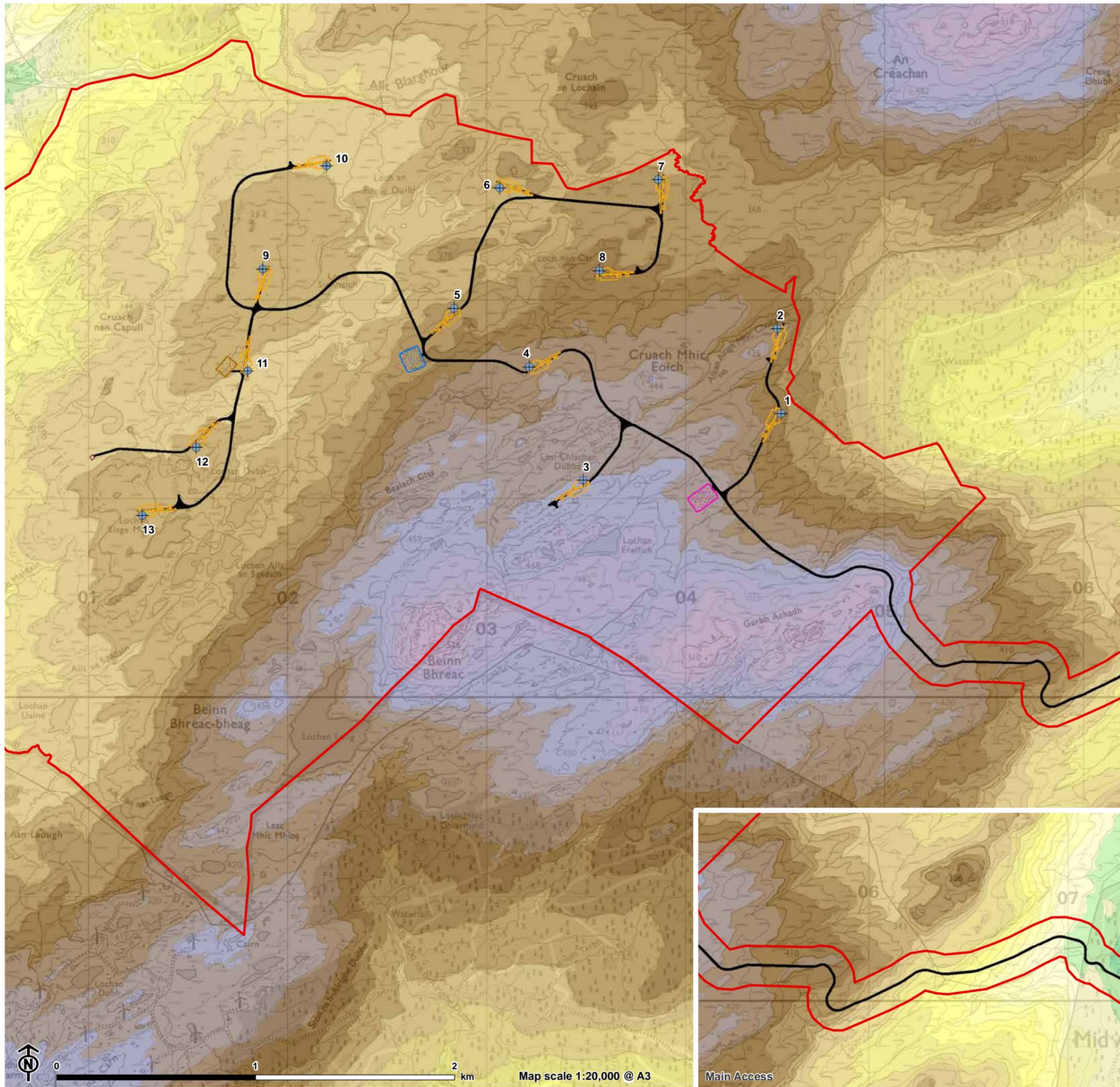
This monitoring should be undertaken on a quarterly basis in the first year after construction, biannually in the second year after construction and annually thereafter; in the event that unanticipated ground conditions arise during construction, the frequency of these intervals should be reviewed, revised and justified accordingly.

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Figure 7.4.1: Elevation



- Site boundary
- Turbine
- Existing access track
- Proposed track
- Borrow pit
- Temporary construction compound
- Permanent compound including substation and BESS
- Temporary hardstanding
- Permanent hardstanding
- Permanent met mast

Elevation (m)

- 140 - 160
- 160 - 180
- 180 - 200
- 200 - 220
- 220 - 240
- 240 - 260
- 260 - 280
- 280 - 300
- 300 - 320
- 320 - 340
- 340 - 360
- 360 - 380
- 380 - 400
- 400 - 420
- 420 - 440
- 440 - 460
- 460 - 480
- 480 - 500
- 500 - 520



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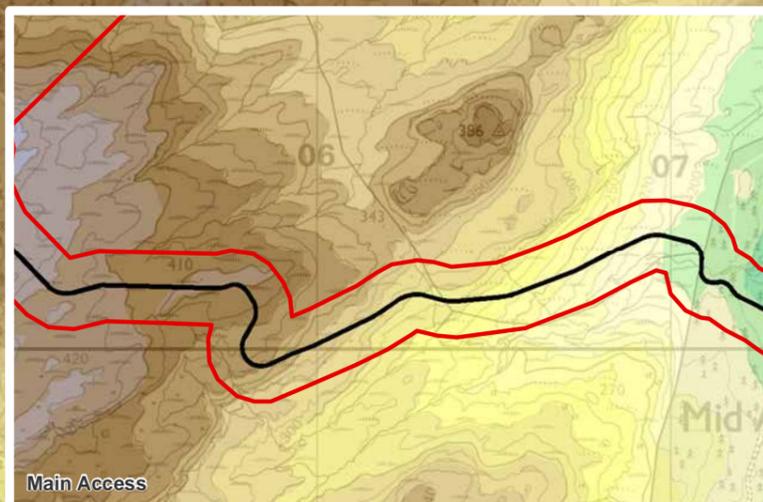
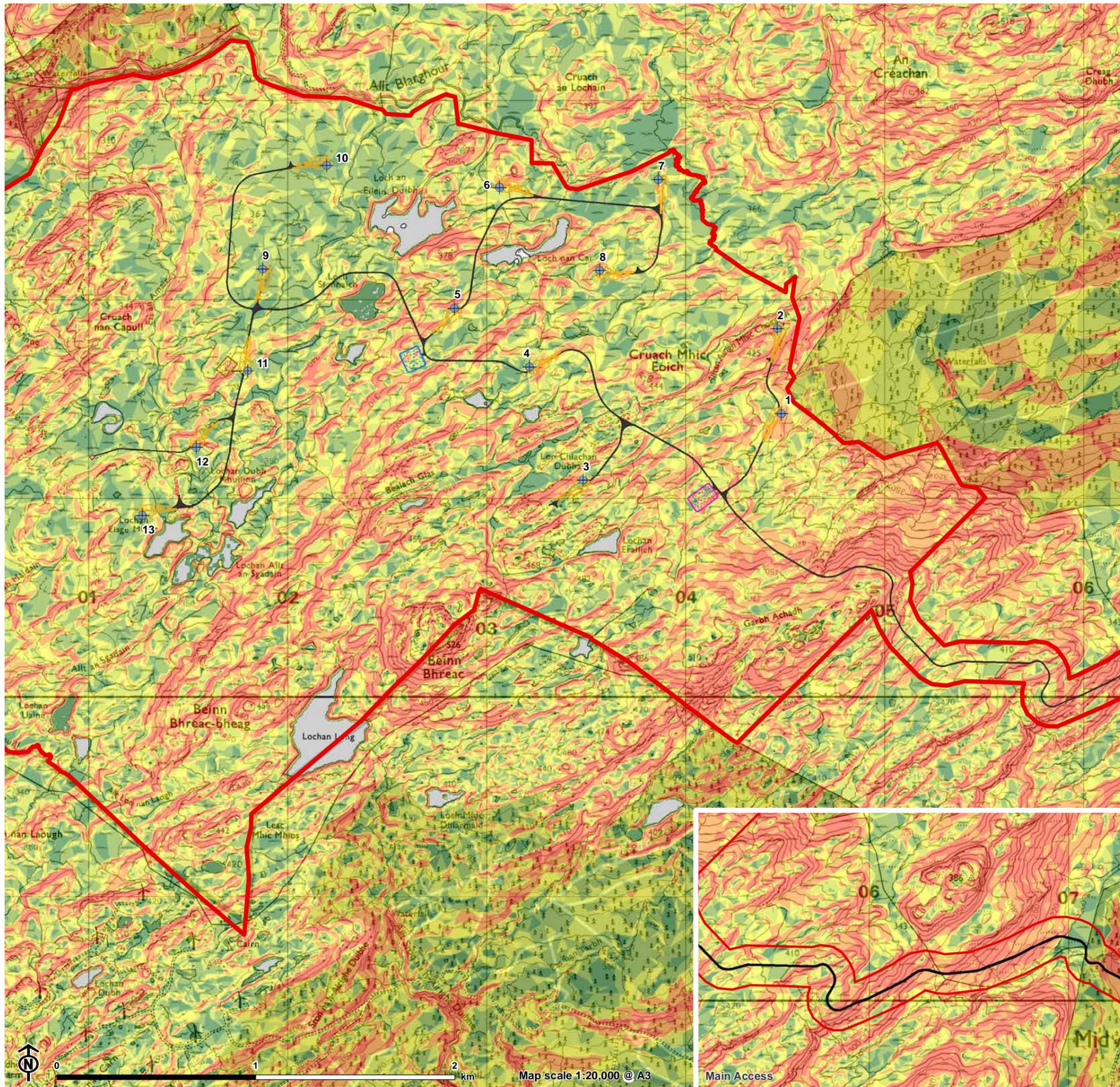


Figure 7.4.2: Slope Angle



- Site boundary
 - Turbine
 - Existing access track
 - Proposed track
 - Borrow pit
 - Temporary construction compound
 - Permanent compound including substation and BESS
 - Temporary hardstanding
 - Permanent hardstanding
 - Permanent met mast
- Slope (in degrees)**
- Slope angle (degrees)**
- 0.0 - 2.5
 - >2.5 - 5.0
 - >5.0 - 7.5
 - >7.5 - 10.0
 - >10.0 - 15.0
 - >15.0

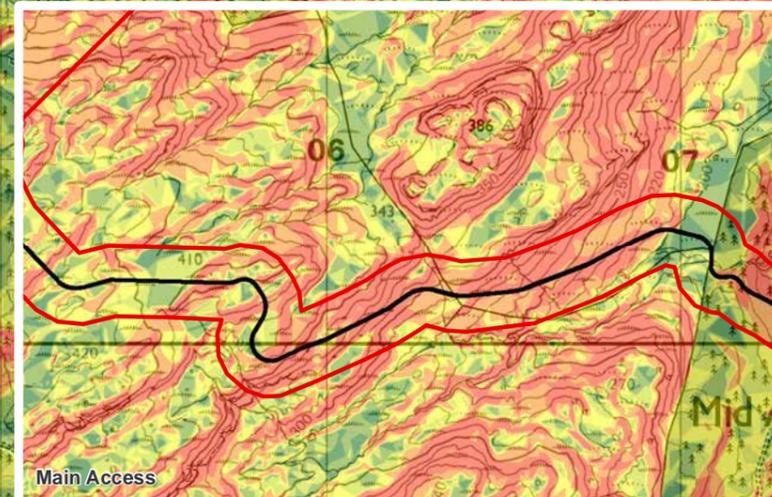
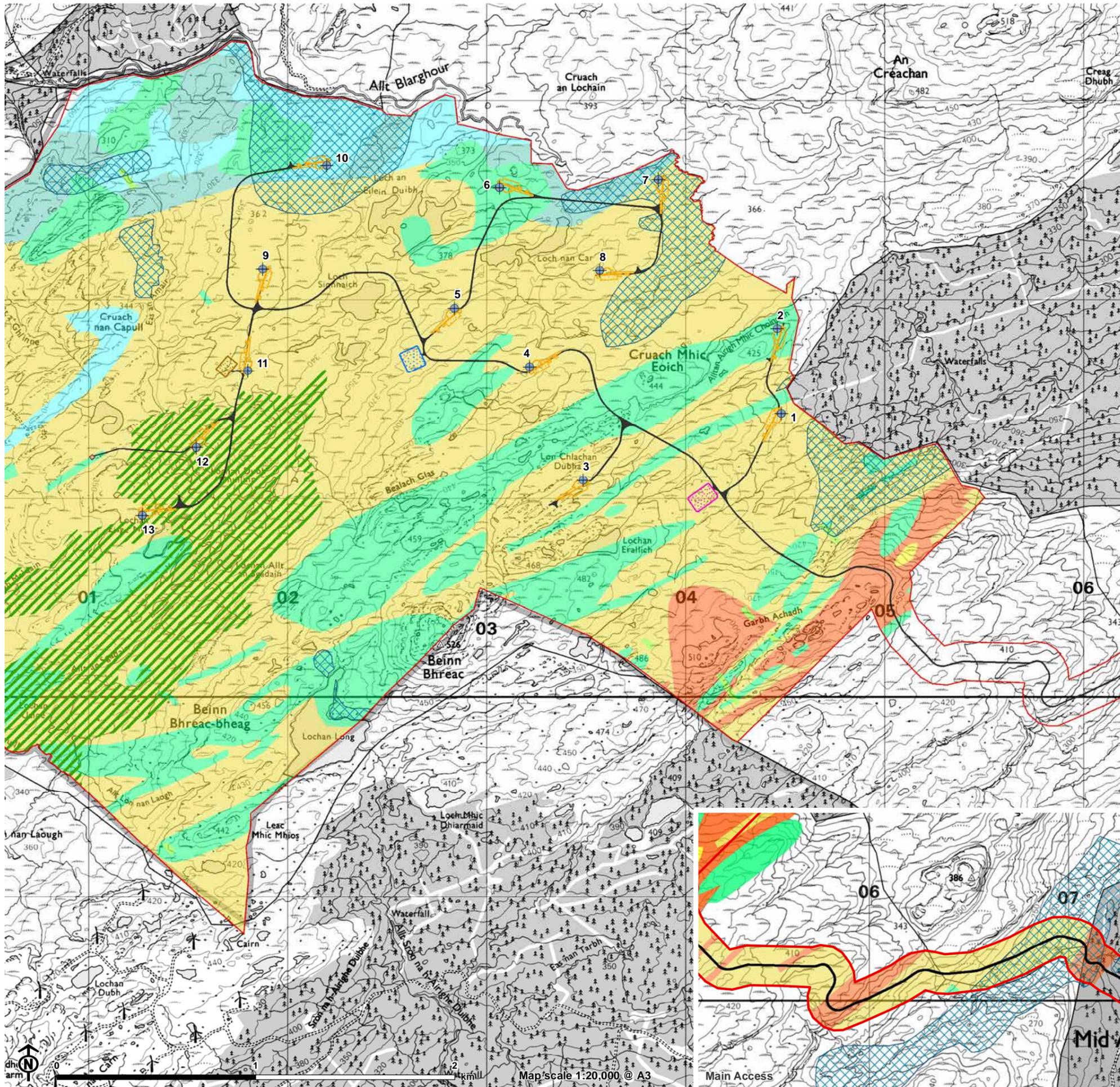
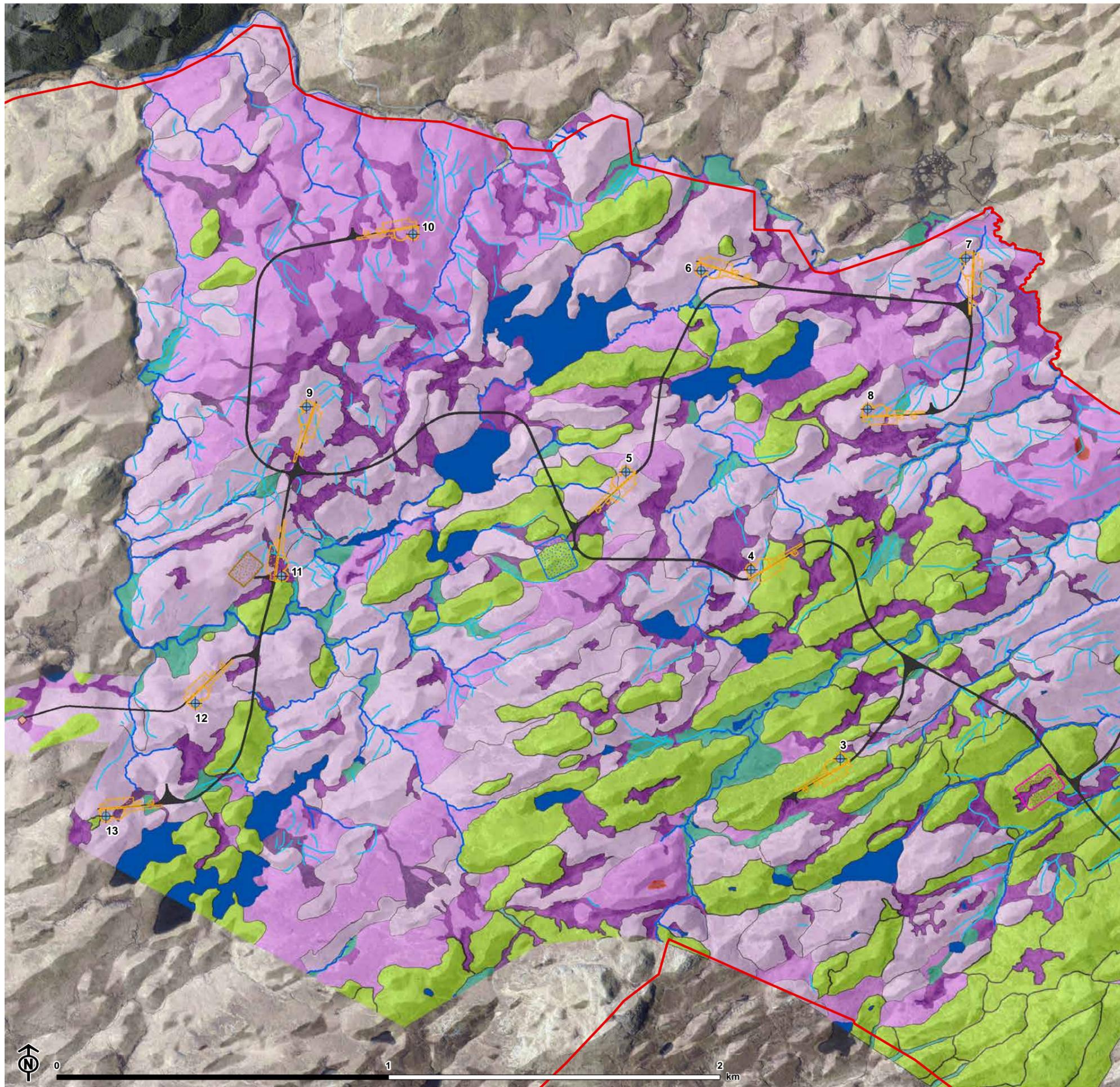


Figure 7.4.3: Superficial and Bedrock Geology



- Site boundary
 - Turbine
 - Existing access track
 - Proposed track
 - Borrow pit
 - Temporary construction compound
 - Permanent compound including substation and BESS
 - Temporary hardstanding
 - Permanent hardstanding
 - Permanent met mast
- Superficial Geology**
- Alluvium - Clay, Silt, Sand and Gravel
 - Hummocky (Moundy) Glacial Deposits - Diamicton, Sand and Gravel
 - River Terrace Deposits - Gravel, Sand, Silt and Clay
 - Till, Devensian - Diamicton
- Bedrock Geology**
- Argyll Group - Quartzite, Metalimestone and Phyllitic Semipelite
 - Crinan Grit Formation – Metalimestone
 - Crinan Grit Formation – Quartzite
 - Dalradian Supergroup - Metagabbro and Metamicrogabbro
 - Mull Dyke-Swarm - Basalt and Microgabbro
 - Scottish Highland Siluro-Devonian Calc-Alkaline Minor Intrusion Suite (Other Than Dykes) – Felsite
 - Tayvallich Slate And Limestone Formation –
 - Tayvallich Slate And Limestone Formation - Pelite, Graphitic

Figure 7.4.4: Geomorphology, Hydrology and Land Use (Sheet A)



- Site boundary
 - Turbine
 - Existing access track
 - Proposed track
 - Borrow pit
 - Temporary construction compound
 - Permanent compound including substation and BESS
 - Temporary hardstanding
 - Permanent hardstanding
 - Permanent met mast
- Geomorphology**
- Afforested peatland
 - Instability feature
 - Inter-ridge trough
 - Watercourse
 - Ridge (rock outcrop)
 - Ridge (thin peat)
 - Planar peat
 - Hagged peat
 - Dendritic drainage / gullies
 - Water body
 - Moor drains
 - Watercourses

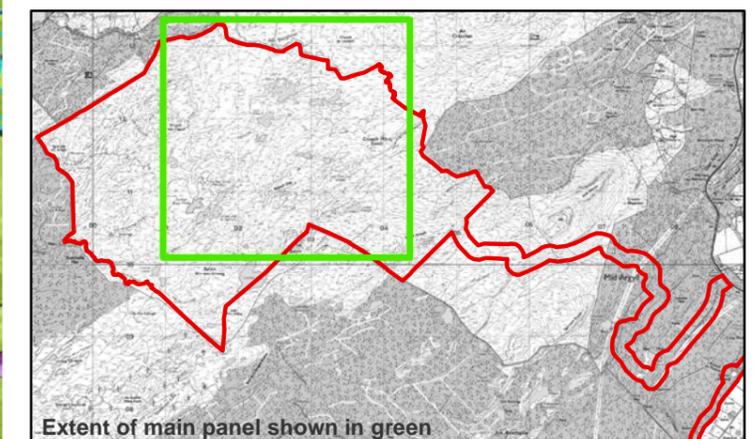
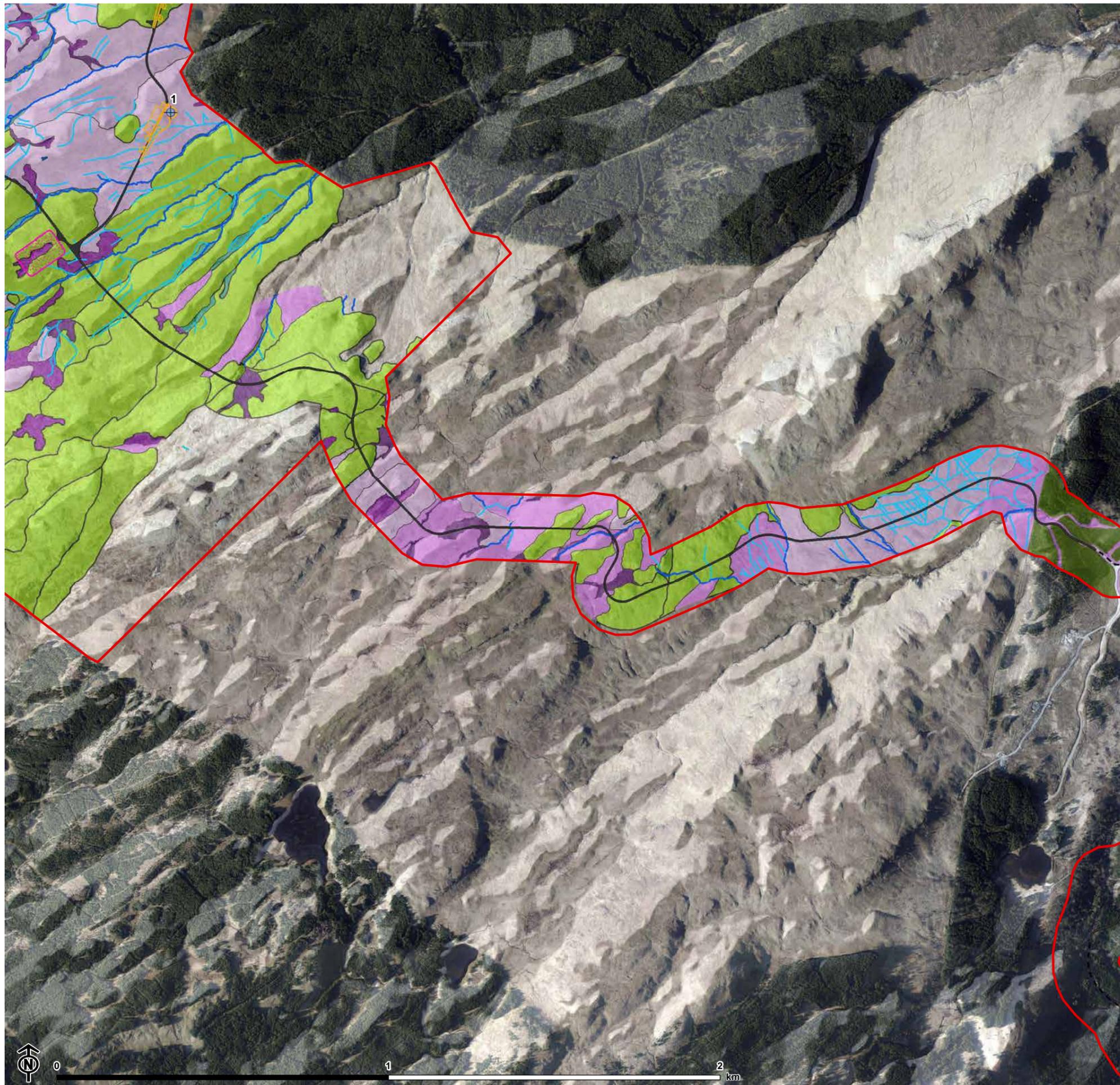


Figure 7.4.4: Geomorphology, Hydrology and Land Use (Sheet B)



- Site boundary
 - Turbine
 - Existing access track
 - Proposed track
 - Borrow pit
 - Temporary construction compound
 - Permanent compound including substation and BESS
 - Temporary hardstanding
 - Permanent hardstanding
 - Permanent met mast
- Geomorphology**
- Afforested peatland
 - Instability feature
 - Inter-ridge trough
 - Watercourse
 - Ridge (rock outcrop)
 - Ridge (thin peat)
 - Planar peat
 - Hagged peat
 - Dendritic drainage / gullies
 - Water body
 - Moor drains
 - Watercourses

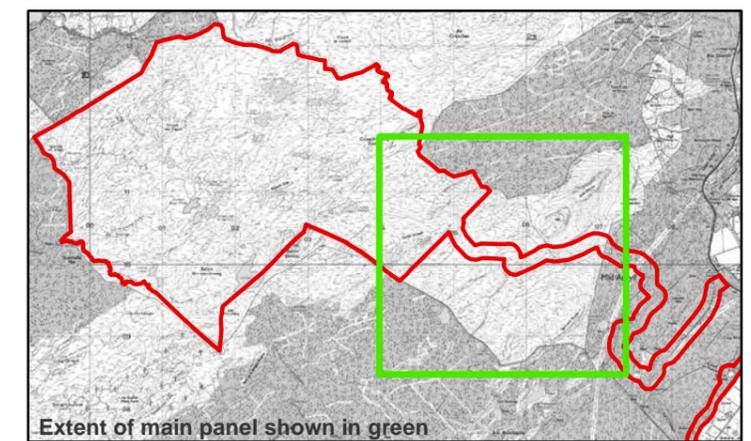
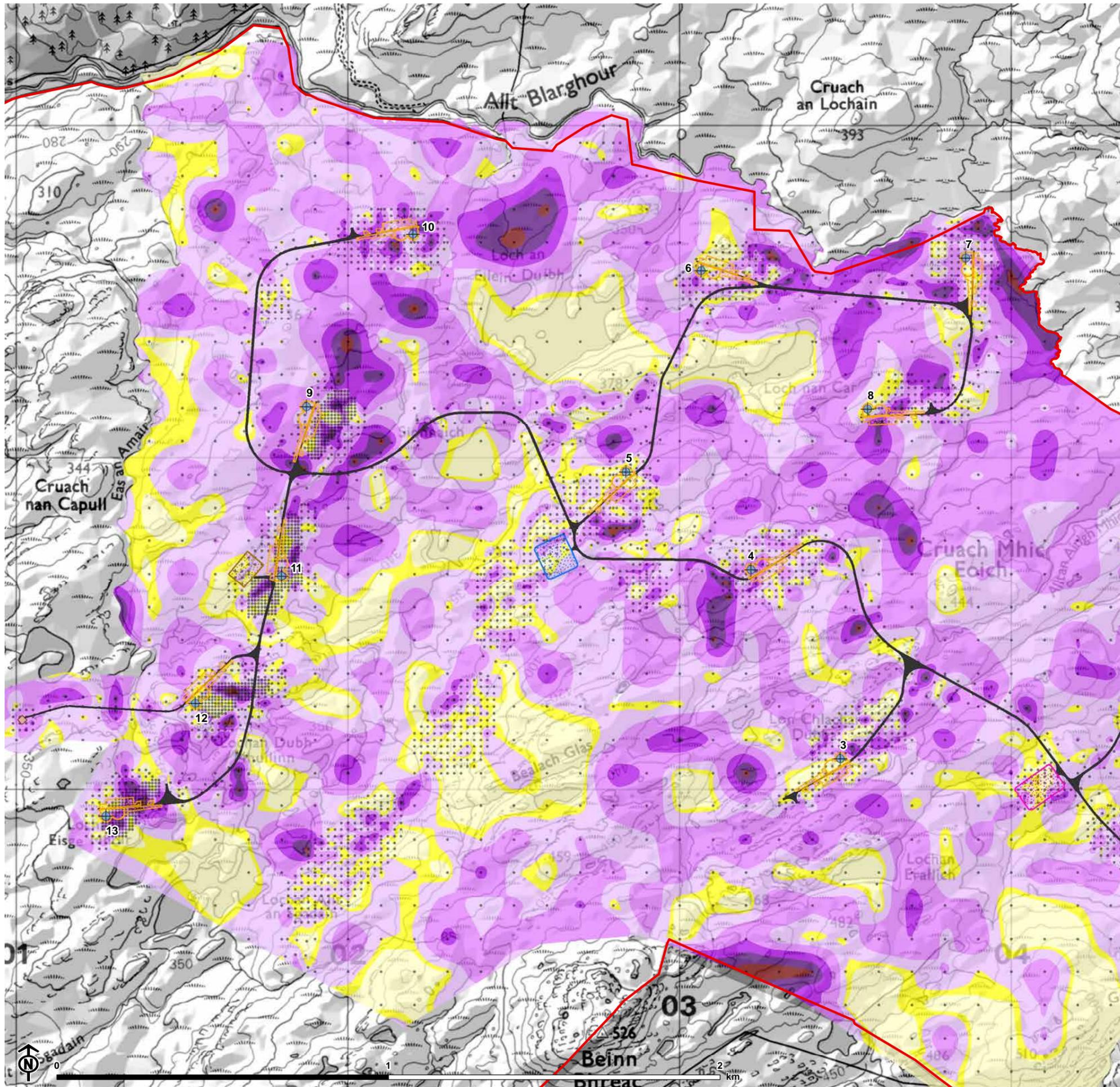


Figure 7.4.5: Peat Depths (Sheet A)



- Site boundary
 - Turbine
 - Existing access track
 - Proposed track
 - Borrow pit
 - Temporary construction compound
 - Permanent compound including substation and BESS
 - Temporary hardstanding
 - Permanent hardstanding
 - Permanent met mast
- Peat depth (cm)**
- ≤ 0.35
 - >0.35 - 0.50
 - >0.50 - 1.00
 - >1.00 - 2.00
 - >2.00 - 3.00
 - >3.00 - 4.00
 - >4.00 - 5.00
 - Probe location

Carbon and Peatland (2016) Map

- Class 2
- Class 5

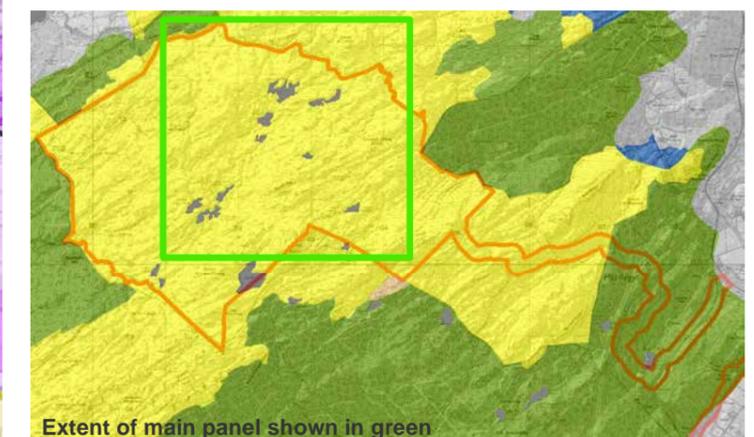
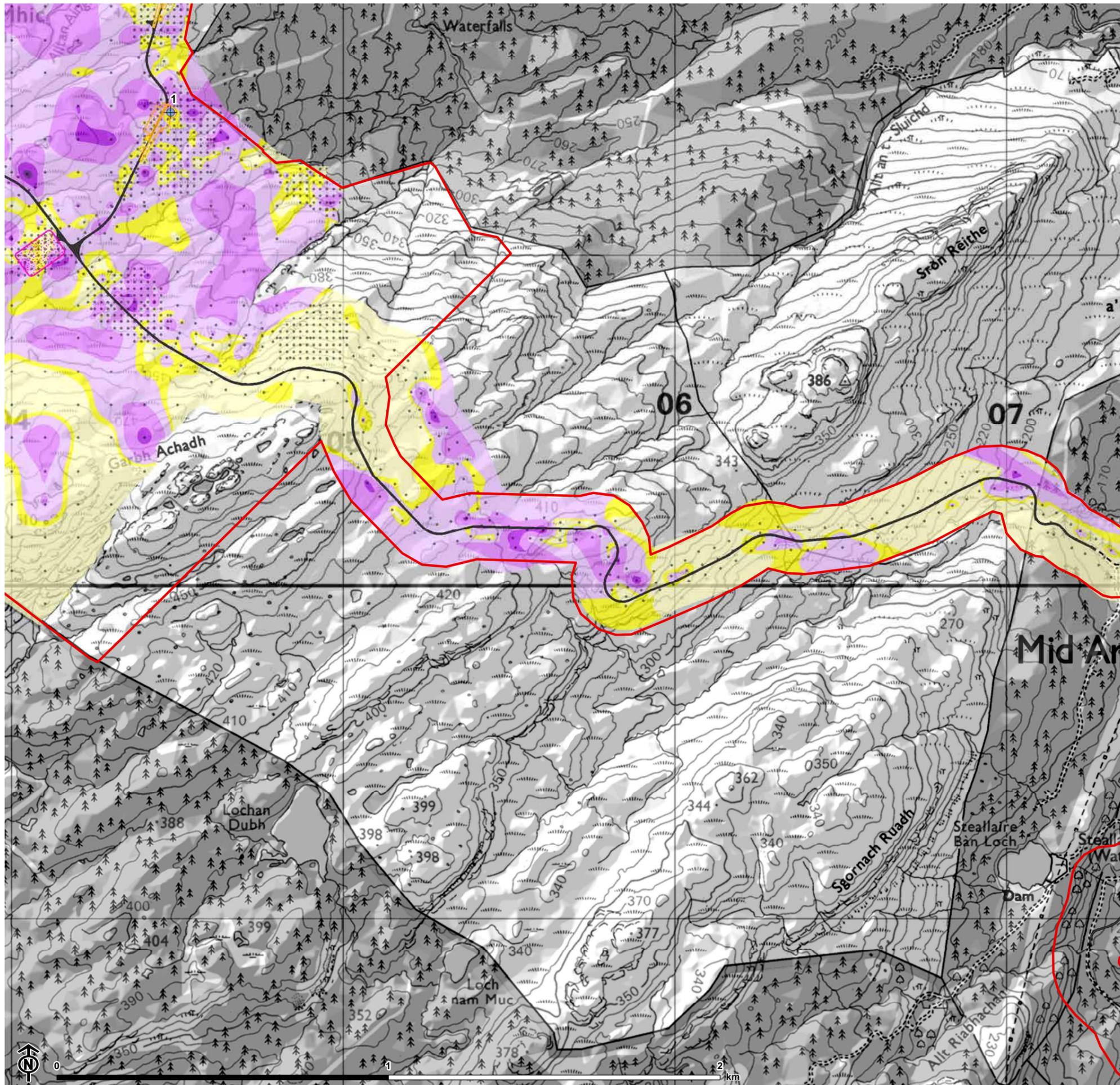


Figure 7.4.5: Peat Depths (Sheet B)



- Site boundary
 - Turbine
 - Existing access track
 - Proposed track
 - Borrow pit
 - Temporary construction compound
 - Permanent compound including substation and BESS
 - Temporary hardstanding
 - Permanent hardstanding
 - Permanent met mast
- Peat depth (cm)**
- ≤ 0.35
 - >0.35 - 0.50
 - >0.50 - 1.00
 - >1.00 - 2.00
 - >2.00 - 3.00
 - >3.00 - 4.00
 - >4.00 - 5.00
- Probe location

Carbon and Peatland (2016) Map

- Class 2
- Class 5

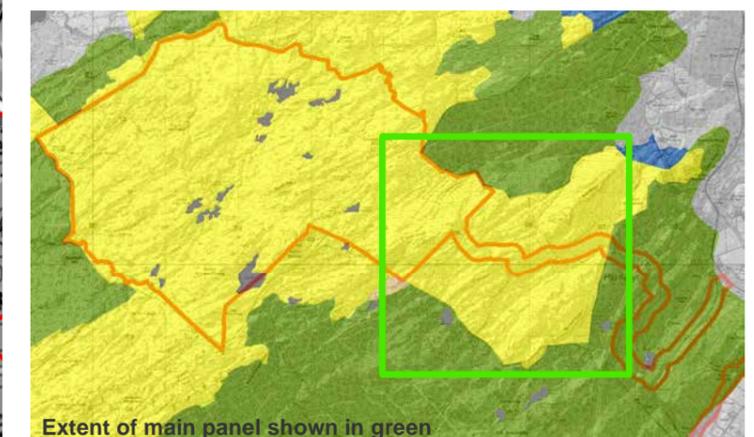
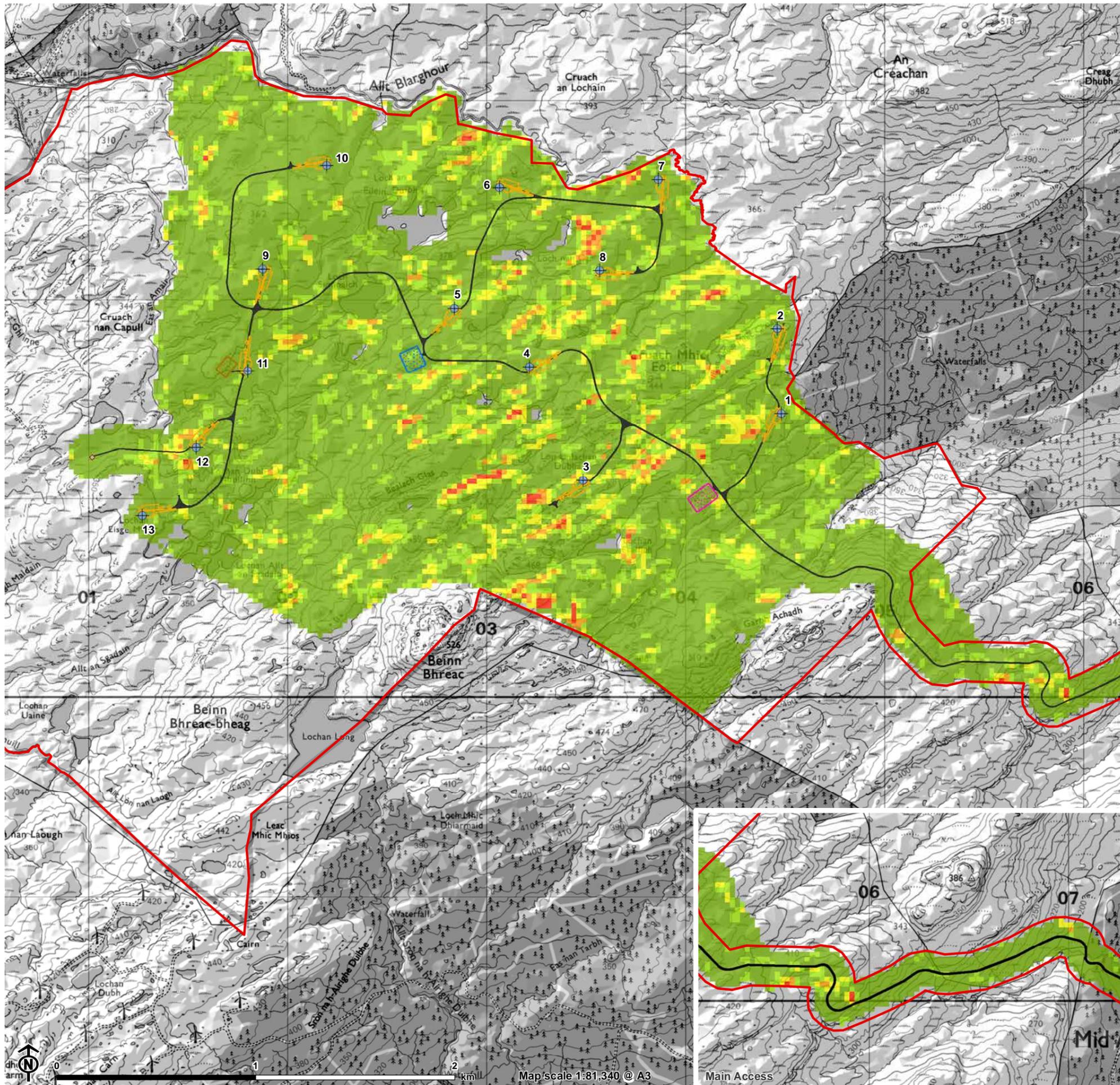
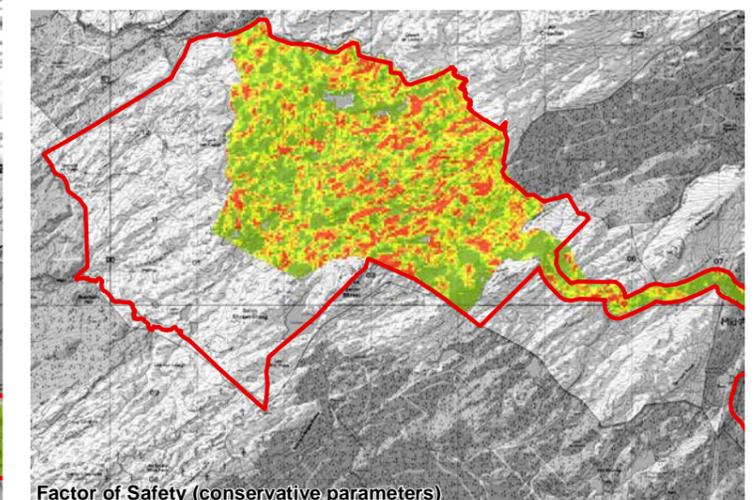


Figure 7.4.6: Factor of Safety



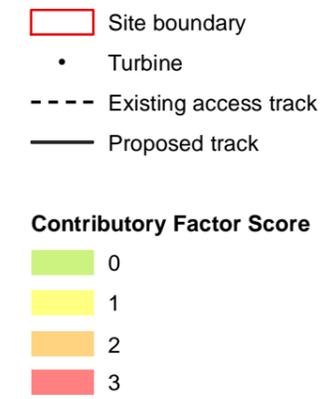
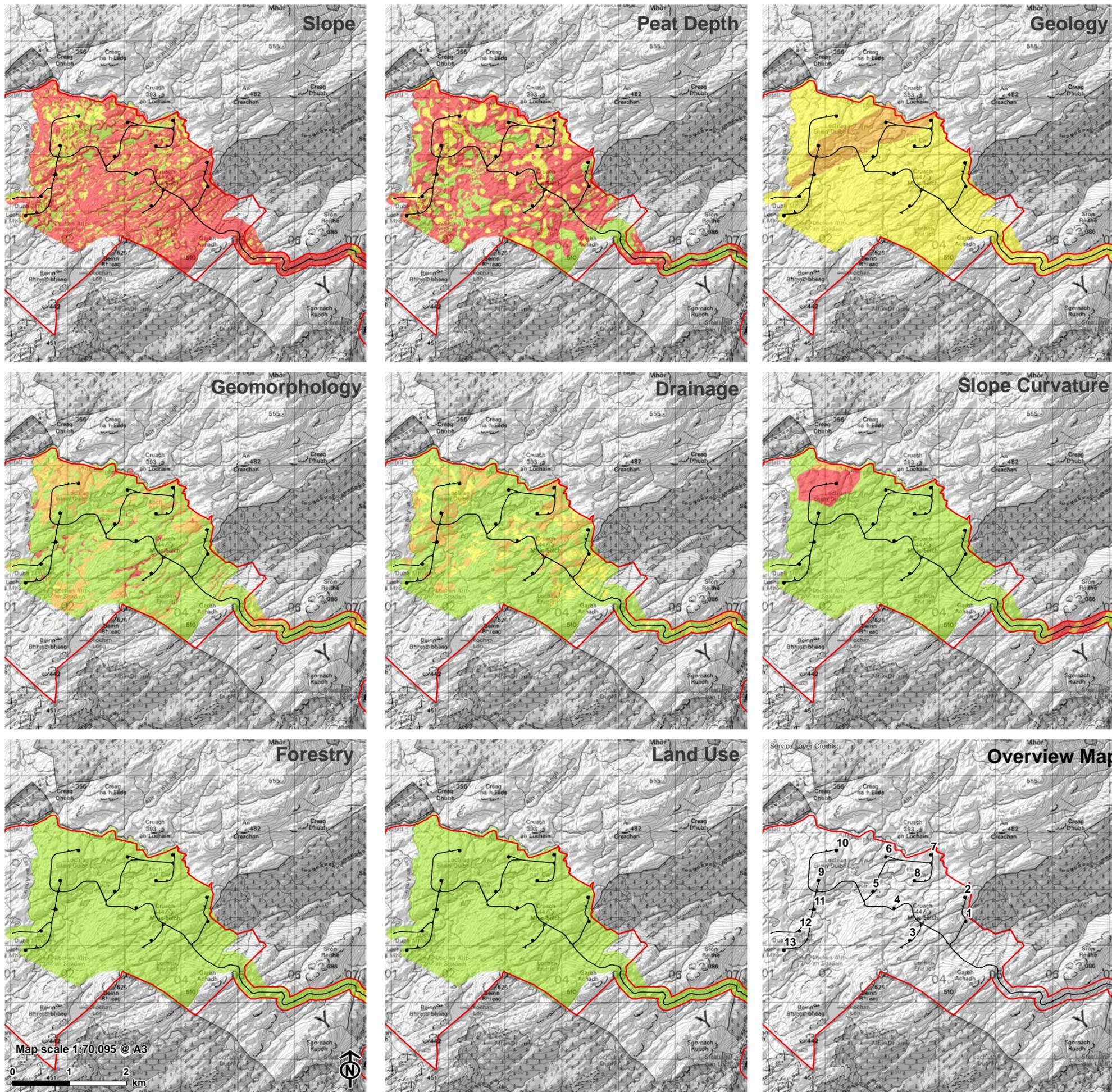
- Site boundary
- Turbine
- Existing access track
- Proposed track
- Borrow pit
- Temporary construction compound
- Permanent compound including substation and BESS
- Temporary hardstanding
- Permanent hardstanding
- Permanent met mast

- Factor of Safety**
- 0.0 - 1.0 "Unstable"
 - 1.0 - 1.4 "Marginally Stable"
 - 1.4 - 2.0 "Stable"
 - 2.0 - 3.0 "Stable"
 - > 3.0 "Stable"



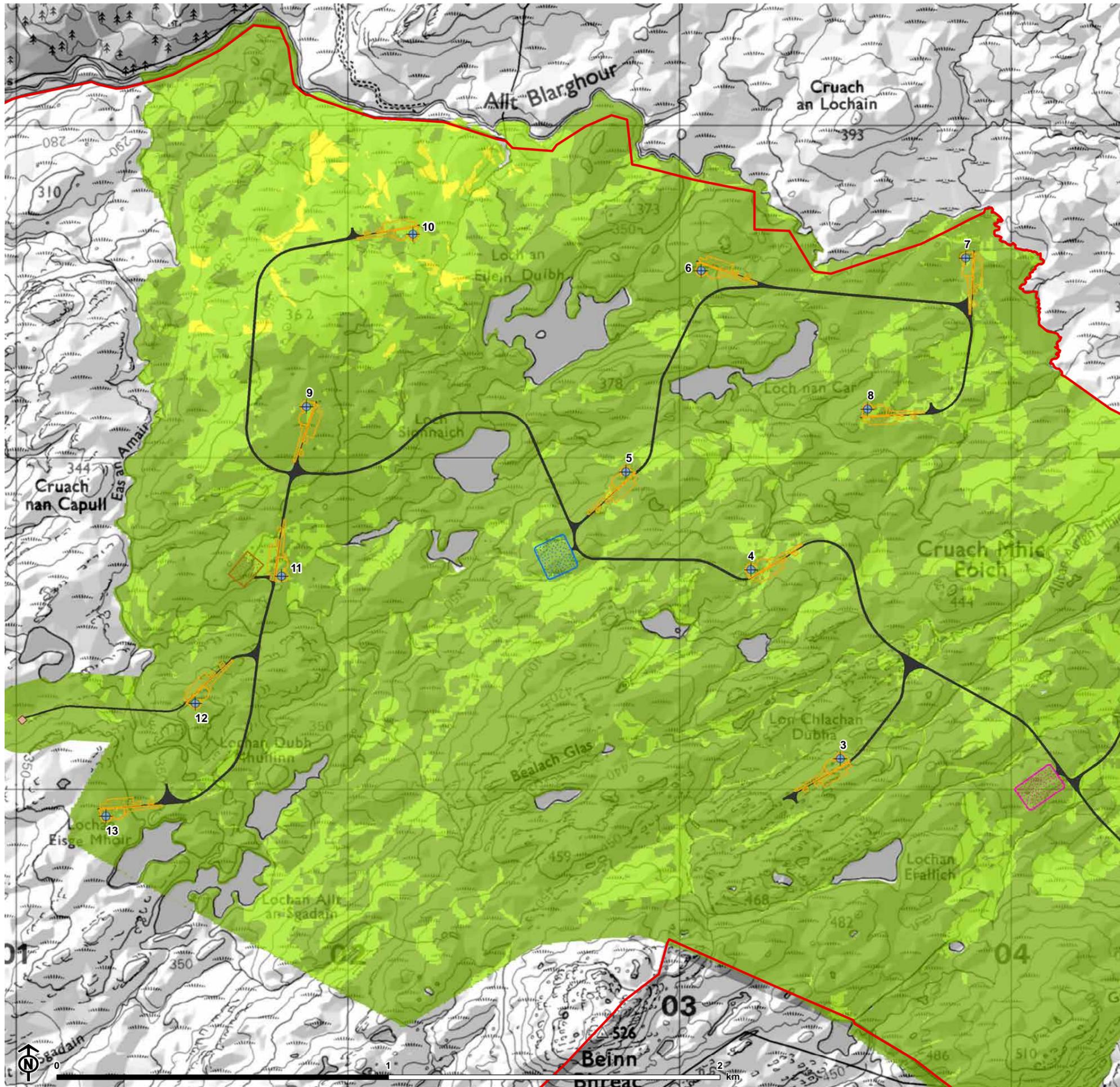
Factor of Safety (conservative parameters)

Figure 7.4.7: Contributory Factors



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Figure 7.4.8: Peat Slide Likelihood (Sheet A)



- Site boundary
- Turbine
- Existing access track
- Proposed track
- Borrow pit
- Temporary construction compound
- Permanent compound including substation and BESS
- Temporary hardstanding
- Permanent hardstanding
- Permanent met mast

Likelihood Score

- <= 7 (Very Low)
- 8 - 12 (Low)
- 13 - 17 (Moderate)
- 18 - 21 (High)
- > 21 (Very High)

Note: there are no High or Very High likelihood areas present within the Site

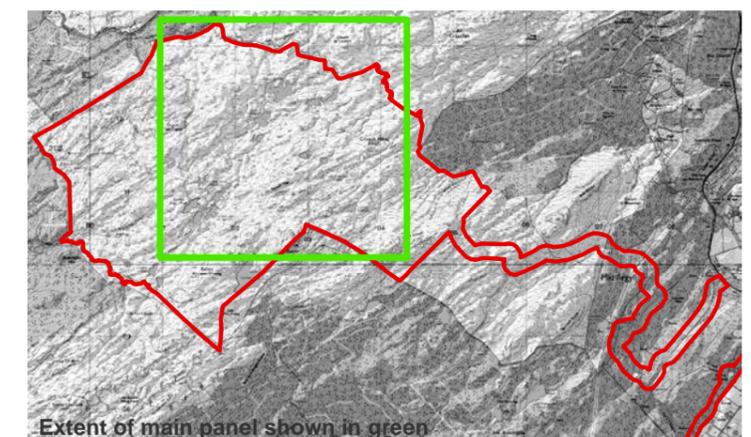
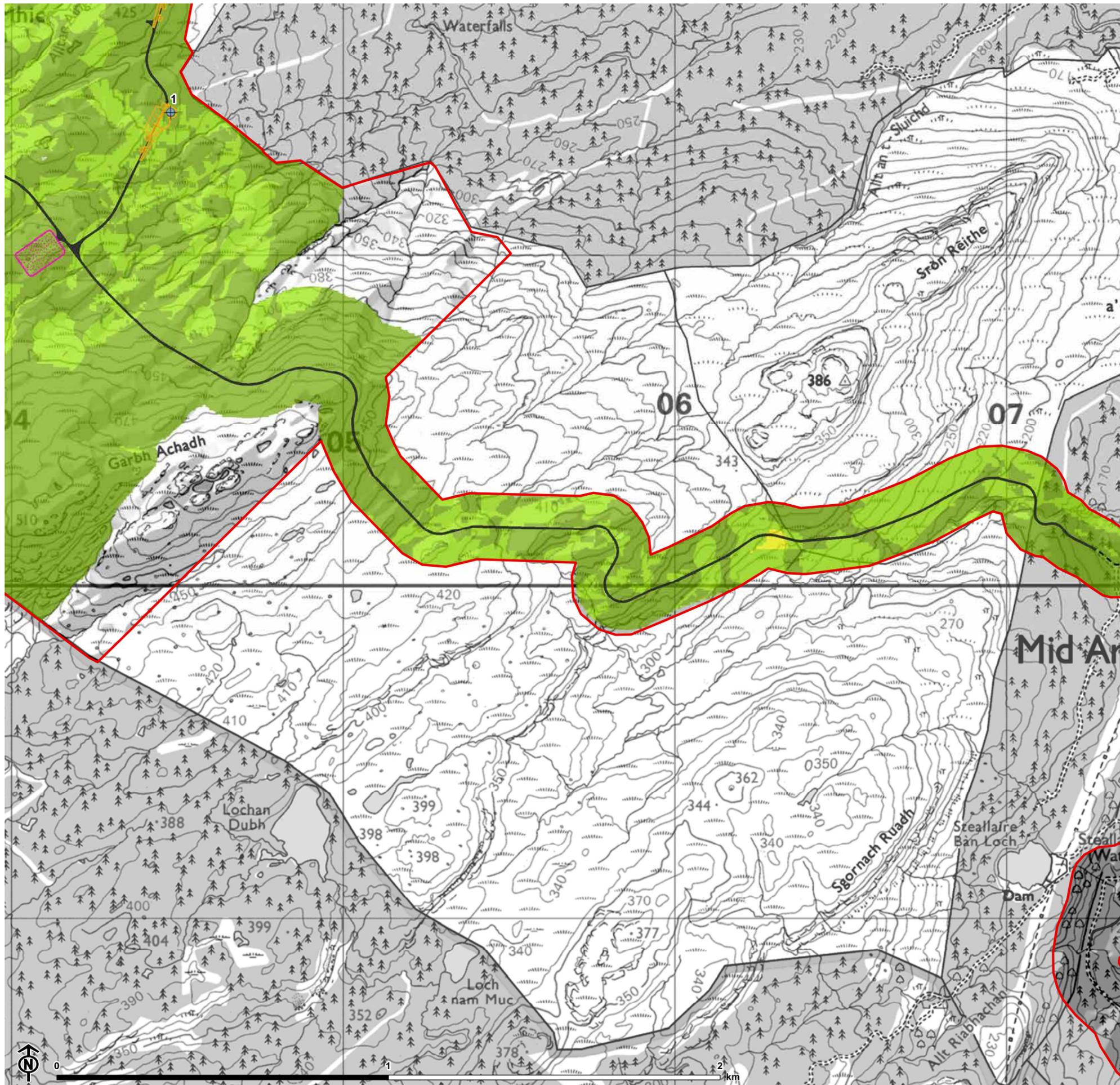


Figure 7.4.8: Peat Slide Likelihood (Sheet B)

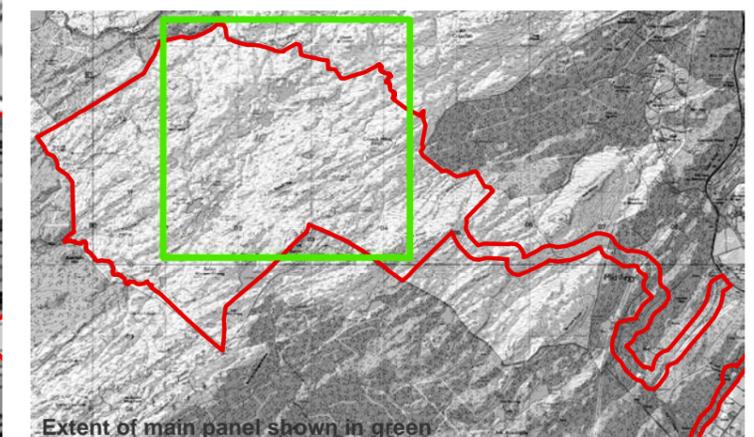


- Site boundary
- Turbine
- Existing access track
- Proposed track
- Borrow pit
- Temporary construction compound
- Permanent compound including substation and BESS
- Temporary hardstanding
- Permanent hardstanding
- Permanent met mast

Likelihood Score

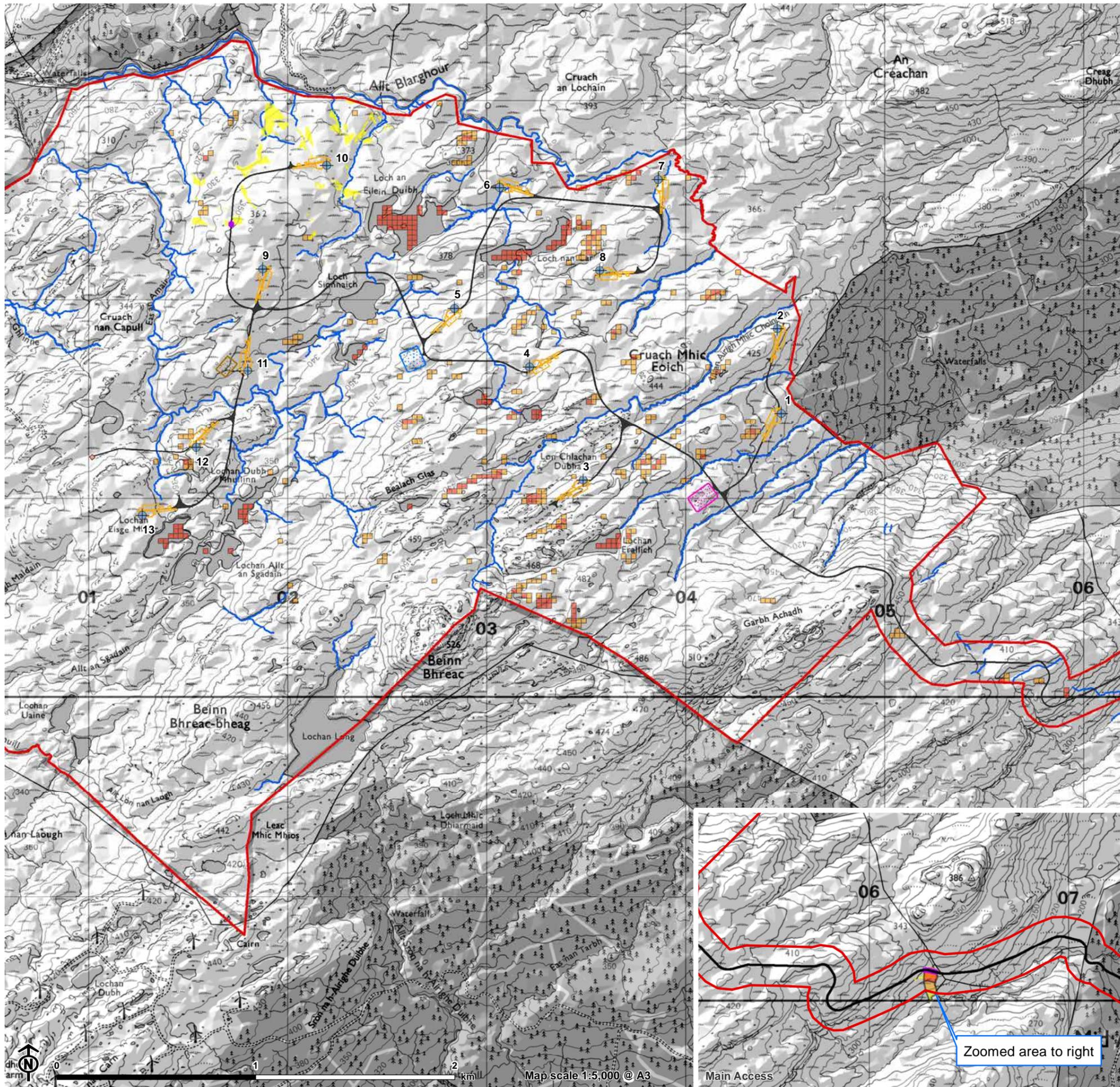
- <= 7 (Very Low)
- 8 - 12 (Low)
- 13 - 17 (Moderate)
- 18 - 21 (High)
- > 21 (Very High)

Note: there are no High or Very High likelihood areas present within the Site



Extent of main panel shown in green

Figure 7.4.9: Source Zones, Runout and Calculated Risk



- Site boundary
 - Turbine
 - Existing access track
 - Proposed track
 - Borrow pit
 - Temporary construction compound
 - Permanent compound including substation and BESS
 - Temporary hardstanding
 - Permanent hardstanding
 - Permanent met mast
- Likelihood Score**
- 13 - 17 (Moderate)
 - 18 - 21 (High)
 - > 21 (Very High)
- Factor of Safety**
- 0.0 - 1.0 "Unstable"
 - 1.0 - 1.4 "Marginally Stable"
- Receptors**
- Existing access track
- Source Zone**
- Source Zone

