Appendix 8.4: Peat Landslide Hazard and Risk Assessment

Consulting Report

Appendix 8.4 - Peat Landslide Hazard and Risk Assessment
Dunside Wind Farm

Scottish Borders
EDF Energy Renewables Ltd

21-LUC-031-D-001v02

07/06/2023

Prepared for
Land Use Consultants

Client
EDF Energy Renewables ltd

DOCUMENT CONTROL

Version	Description	Prepared by	Approved by	Date
01	Issued as draft for review	AM	LM	12/05/2023
02	Issue	AM	LM	07/06/2023

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1. INTRODUCTION

1.1. Background

EDF Energy Renewables Ltd. (the Applicant) are seeking consent under Section 36 of the Electricity Act 1989 for construction of the Dunside Wind Farm, Scottish Borders (hereafter the 'Proposed Development'). The site for the Proposed Development lies approximately 6 km north of Westruther and 7 km west of Longformacus and is approximately 20 km^2 (c. 2,000 ha) in area (Plate 1.1). The site is bordered to the west by the operational Fallago Rig Wind Farm (also operated by EDF), to the north and south by open fells within the Lammermuir Hills and to the east by rolling hills which drain to Watch Water Reservoir.

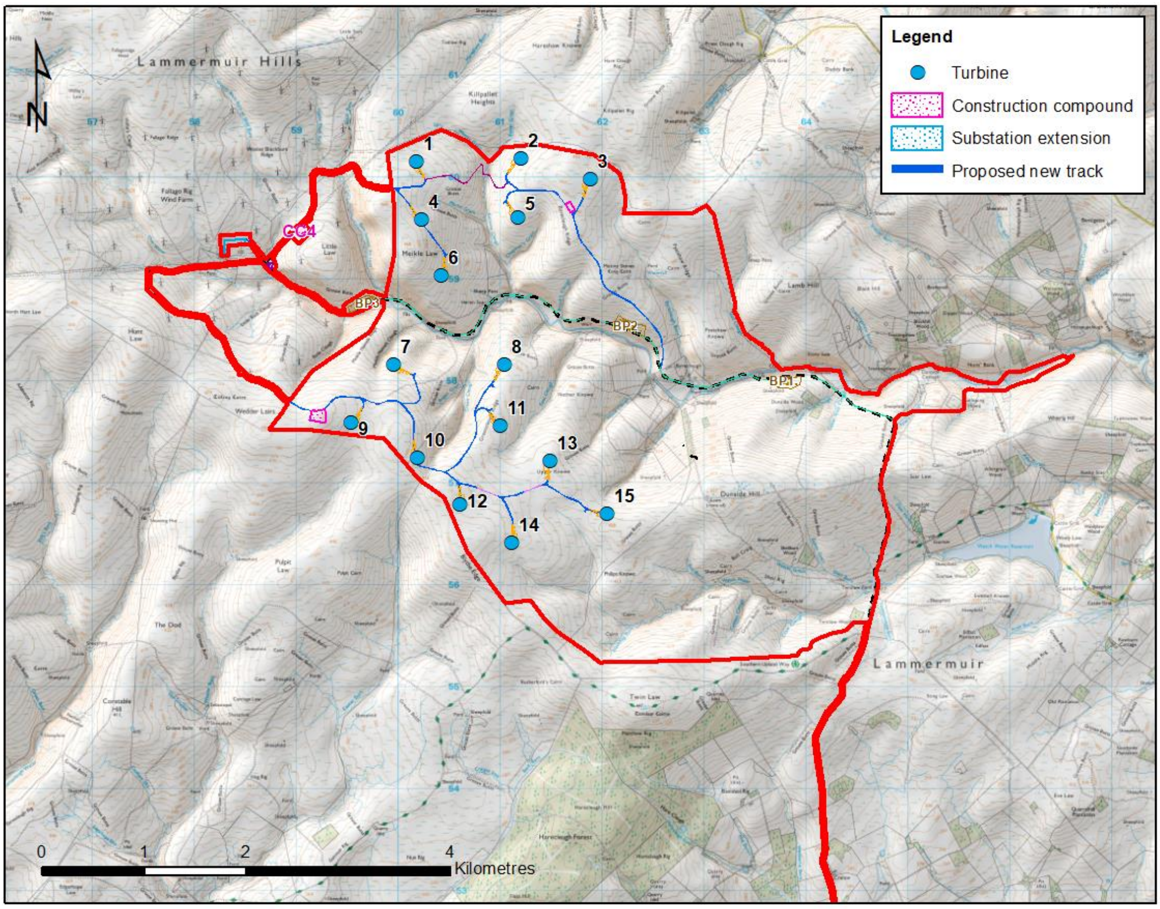

Plate 1.1 Proposed location of the Proposed Development

The Proposed Development will comprise:

- Up to 15 wind turbines, each with a maximum tip height of 220 m (with an external transformer kiosk);
- Crane hardstandings adjacent to each turbine position;
- Four new watercourse crossings and associated infrastructure;
- Approximately 15 km of proposed wind farm tracks and approximately 1.1 km of proposed light vehicle track;
- Approximately 17.5 km of existing access tracks (including areas of widening/upgrading);
- Onsite underground electrical cables and cable trenches;

- Control building and extension to Fallago Rig existing substation;
- A 20 MW battery storage area;
- Four temporary construction compounds (two existing compounds which will remain in situ following completion of the Proposed Development, and two proposed which will be restored following construction), including laydown areas and car parking; and
- Up to three temporary borrow pits which will be closed and reinstated following completion of construction.

The infrastructure will be subject to a micro-siting allowance of 100 m

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.

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):

i. 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.

ii. An assessment of evidence for past landslide activity and present-day instability e.g. pre-failure indicators.

iii. A qualitative or quantitative assessment of the potential for or likelihood of future peat landslide activity (or a landslide susceptibility or hazard assessment).

iv. Identification of receptors (e.g. habitats, watercourses, infrastructure, human life) exposed to peat landslide hazards; and

v. 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.

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 8.3) and have been informed by results from the Peat Survey (EIA Report Appendix 8.2). Where relevant information is available elsewhere in the Environmental Impact Assessment Report (EIA Report), 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:

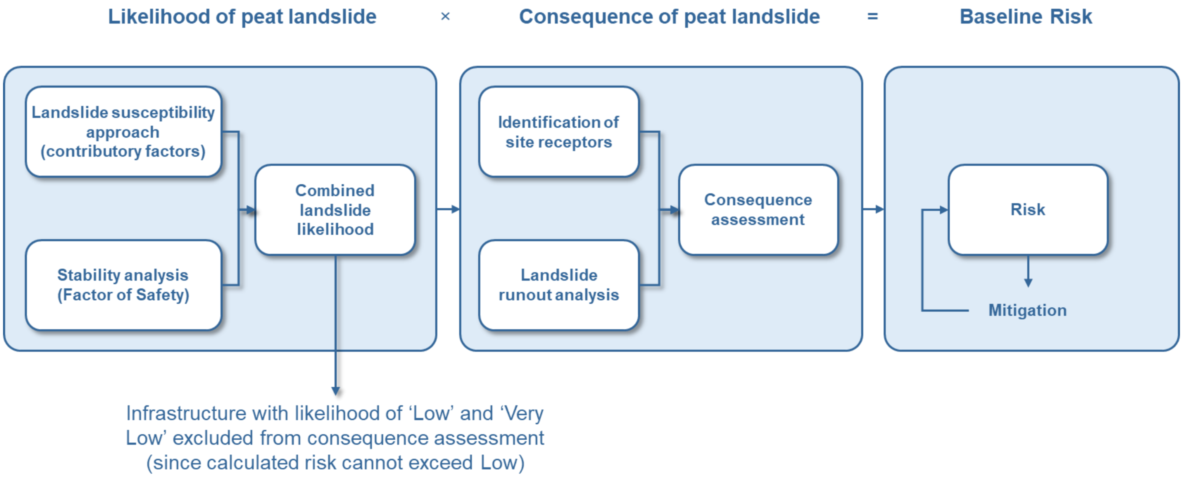

Plate 1.2 Risk assessment approach

1.5. Team competencies

This PLHRA has been undertaken by a chartered geologist with 25+ years experience of mapping and interpreting peatland terrains and peat instability features. Geomorphological walkover survey was undertaken by the same individual. Peat depth probing was undertaken by Kaya Consulting, a highly experienced peatland survey team, and additional site observations and photographs were made available from these surveys to the PLHRA team.

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 turbary (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. A peat landslide was also reported in 2015 near the site of a proposed road for the Viking Wind Farm on Shetland (The Shetland Times, 2015) though this was not in association with construction works.

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).

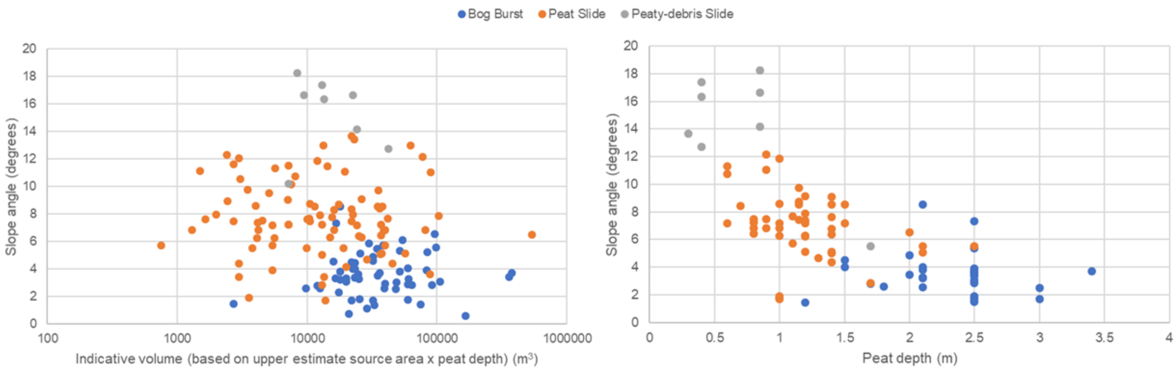

Plate 2.2 Reported slope angles and peat depths associated with peat slides and bog bursts (from literature review of locations, depths and slope angles, after Mills, 2002)

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 1.0 m and up to 10 m) 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. Bog bursts are rarely (if ever) reported in Scotland other than in the Western Isles (e.g. Bowes, 1960).

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. There are no published failures or news reports of landslides in proximity to the Proposed Development and none have been reported in association with the neighbouring Fallago Rig Wind Farm nor are visible on muti-epoch satellite imagery for that site.

2.2.1. Factors Contributing to Peat Instability

Peat landslides are caused by a combination of factors – triggering factors and reconditioning 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:

i. Impeded drainage caused by a peat layer overlying an impervious clay or mineral base (hydrological discontinuity).

ii. A convex slope or a slope with a break of slope at its head (concentration of subsurface flow).

iii. Proximity to local drainage, either from flushes, pipes or streams (supply of water).

iv. Connectivity between surface drainage and the peat/impervious interface (mechanism for generation of excess pore pressures).

v. 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).

vi. Increase in mass of the peat slope through peat formation, increases in water content or afforestation.

vii. 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.

viii. Loss of surface vegetation and associated tensile strength (e.g. by burning or pollution induced vegetation change).

ix. Increase in buoyancy of the peat slope through formation of sub-surface pools or water-filled pipe networks or wetting up of desiccated areas.

x. 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':

i. Intense rainfall or snowmelt causing high pore pressures along pre-existing or potential rupture surfaces (e.g. between the peat and substrate).

ii. Rapid ground accelerations (e.g. from earthquakes or blasting).

iii. Unloading of the peat mass by fluvial incision or by artificial excavations (e.g. cutting).

iv. Focusing of drainage in a susceptible part of a slope by alterations to natural drainage patterns (e.g. by pipe blocking or drainage diversion).

v. 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); and
- 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 Küchler, 2002; Mills, 2002). Typically, it is short-term (seasonal) effects on watercourses that are the primary concern or impacts on public water supply.

3. DESK STUDY

3.1. Topography

The site is located within the Lammermuir Hills in the Scottish Borders and consists of rolling hills ranging between 300 m and 500 m AOD that drain from the north and south towards the west-to-east aligned Dye Water, which flows east out of the site boundary at c. 220 m AOD.

In the north, the main summits are Meikle Law (468 m AOD) in the west (adjacent to Turbines 1, 4 and 6) and Byrecleugh Ridge (c. 440 m AOD) around which Turbines 2, 3 and 5 are distributed. In the south, Wedder Lairs (486 m AOD) sits just outside the southwest corner of the main infrastructure area and a series of low un-named summits fall gentled to c. 460 m AOD at Blythe Edge (south of Turbines 12 and 14). A series of broad and sloping interfluves (or ridges) fall towards the valley floor, each of which is drained by a minor, and usually named, watercourse (see section 3.3 below, Plate 3.1 and Figure 8.4.1).

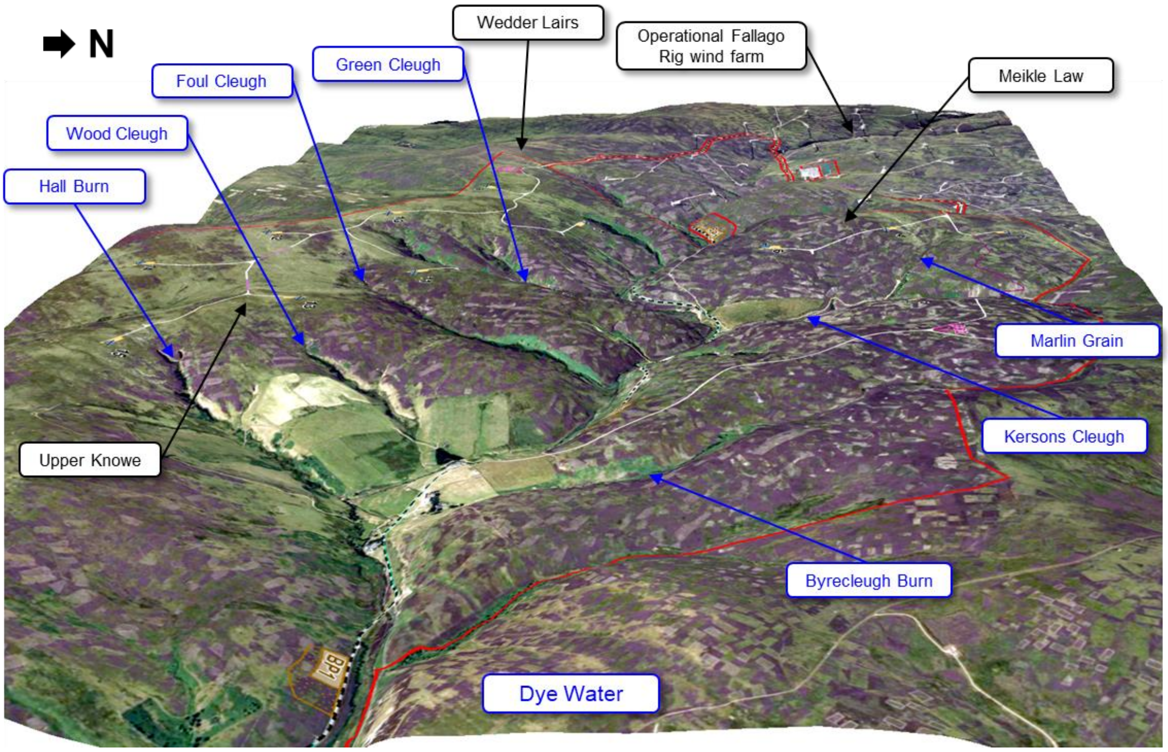

Plate 3.1 Perspective view of site (note 2x vertical exaggeration), the strong patterning associated with muirburn is clearly visible in the heather dominated (purple) upper slopes

Figure 8.4.2 shows slope angles derived from resampled publicly available LiDAR data at a raster resolution of 5 m. The broad summit bridge bordering the southern site boundary hosts gentle slopes of <2.5° which steeper relatively rapidly into the sideslopes of the interfluves that drain to the Dye Water, slope angles frequently exceeding 15° on these steep valley sides. The northern half of the site is split in two by Kersons Cleugh, again with gentle slopes on the summits to the north of Meikle Law and along Byrecleugh Ridge. Due to the severity of the sideslopes below the summits, wind farm infrastructure is concentrated on the gentle upper slopes and traversing of the sideslopes by tracks has been minimised. The slopes are generally rectilinear over much of the site, with relatively pronounced convexities into the valley sides and at the valley heads.

3.2. Geology

Figure 8.4.3 shows the superficial geology of the site mapped from 1:50,000 scale publicly available BGS digital data and indicates the site to be underlain by peat on the summits and by alluvium in the valley floors. Till is minimal, though a dry clay was identified at the base of a majority of locations cored during the peat depth surveys.

Chapter 8 of the EIA Report notes the bedrock geology of the site to comprise deep marine sedimentary rock (Gala Group Wacke) over the majority of the site with the exception of a small section of the southern access track which are sandstones of the Stratheden Group and Inverclyde Group. Further detail is provided in Chapter 8.

There are no geological designations within the site boundary.

3.3. Hydrology

The site is drained by the Dye Water, which flows east to join Whiteadder Water well outside (approximately 4km) the site boundary. In the main infrastructure area, to the south of the Dye Water, Green Cleugh, Foul Cleugh, Wood Cleugh and Hall Burn drain the southern ridge line and to the north of Dye Water, Kersons Clough (fed by Marlin Grain, Wester Grain, Easter Grain and Chapman's Grain), Brock's Cleugh and Byrecleugh Burn drain the northern hills. The minor tributaries are narrow but steep.

Chapter 8 of the EIA Report describes the sensitivities of the various watercourses, noting that the Dye Water is part of the River Tweed SAC (downstream of its confluence with Kersons Cleugh). Despite this, only the Dye Water was noted to have 'Poor Ecological Potential' by SEPA in 2020.

In addition to the natural watercourses, there are a small number of moor drains, primarily on the southern ridge line, but also on the east facing slopes of Meikle Law (where peat is absent). These total around 10 km in length (see Figure 8.4.4).

Examples of drains and smaller watercourses are shown on Plate 3.2.

3.4. Land Use

Land use is predominantly agricultural with widespread grazing and extensive muirburn to support grouse shooting (lines of grouse butts are marked on the Ordnance Survey sheets for the site and are also visible on the ground). Much of the upper elevations are dominated by heather, and the strong patterning associated with muirburn is very visible in the landscape (see Plates 3.1, 3.2 and Figure 8.4.4).

Other than agricultural uses, there is a network of agricultural boundary walls, informal tracks, farm buildings and dwellings and local quarries used to support construction activities within the valley floor.

3.5. Peat Depth and Character

Peat depth probing was undertaken by Kaya Consulting in multiple phases in accordance with Scottish Government (2017) guidance:

- Phase 1 peat survey was carried out in March 2022 and September 2022.
- Phase 2 peat survey was then carried out in December 2022.
- In total, 3,088 locations were probed for peat depth across Phases 1 and 2.

- 15 cores were collected (at proposed turbine locations).

Plate 3.2 a) Drain above Upper Knowe, b) Eroding drain above Upper Knowe (with headcut), c) eroding head in Hall Burn d) head of Bogan Grain, e) Green Cleugh f) bog pool above Meikl Namels Cleugh

A peat survey report (EIA Report Appendix 8.2) documents the findings of these site investigations and summarises peat depth variation over the site:

- c. 38% of probed locations had depths <0.25 m and c. 43% depths between 0.25 and 0.5 m – these locations comprise organic soil and not peat.
- Of the remaining 19% of locations, c. 16% recorded depths between 0.5 and 1.0 m and the remainder > 1.0 m – the deepest peat on site was 3.8 m and was recorded along the northern

boundary of the site on a saddle between Byrecleugh Ridge and Killpallet Rig (outside and to the north of the site boundary).

A peat depth model was interpolated from the point data within 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).

The peat depth model is shown on Figure 8.4.5 with probing locations superimposed. Peat is generally absent below around 400 m AOD, occurring in saddles and above valley heads. The deepest areas can be found adjacent to Upper Knowe in the south of the site and at the northern site boundary north of Byrecleugh Ridge.

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. Much of the site optimisation occurred during interim layouts 5 to 12 (see Chapter 2 of the EIA Report).

Review of the Carbon and Peatland (2016) Map (inset, Figure 8.4.5) indicates the peat covered summits to be Class 5, i.e. carbon-rich soils but with no peatland habitat. Lower slopes are Class 4, i.e. are unlikely to be associated with peatland habitats. There are no Class 1 or Class 2 priority peatland categories within the site.

3.6. Peatland Geomorphology

Satellite imagery available as an ArcGIS Basemap layer was used to interpret and map features within the site boundary. Additional imagery from different epochs available on both Google Earth™ and bing.com/maps was also referred to in order to validate the satellite imagery interpretation. The resulting geomorphological map (Figure 8.4.4) was subsequently verified during a site walkover undertaken in June 2022 by a Chartered Geologist / peatland geomorphologist with over 25 years' experience of assessing peat landslides. Plates 3.2 to 3.3 show typical features identified during the walkovers.

Figure 8.4.4 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.

Gentle (< 5°) planar summits dominate the upper elevations, below which moderate to steep slopes fall towards the Dye Water, incised into a series of steep valley sides within which the various minor watercourses flow. Minor gullying and erosion is present in various locations typically on the moderate slopes above valleys. Drains occur around the heads of some of the valleys, generally in areas where vegetation indicates localised flushes / diffuse surface drainage. Many of the gully heads have evidence of small scale cracking or minor tears, though none of these features appear to be associated with large-scale instability.

Plate 3.3 a) Typical heather dominated upland plateau in northern half of site, b) contrast between mature heather (foreground), muirburn (centre) and open grassy slopes in organic soils (left), c) Fallago Rig wind farm viewed from site

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:

Risk = Probability of a Peat Landslide x 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 8.4.1 and 8.4.2).

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 thi[...]ion (kPa), γ is the bulk unit weight of saturated peat (kN/m^3), γw 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 (°) and ϕ' is the angle of internal friction of the peat (°). 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 use of cut and fill foundations and tracks across almost the whole construction footprint suggest this is an appropriate approach. 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. 20,930 grid cells were analysed. A 25 m x 25 m cell size was chosen because 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 8.4.6. The more conservative combination (minimum c' and ϕ', inset panel) suggests that the moderate to steep slopes in and around the valleys are of marginal stability, however, there is little or no peat in these locations. The less conservative combination (main panel) indicates the entire site to be stable, which is consistent with observations during field survey and 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.

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)
Effective angle of internal friction (ϕ')	20, 30	Credible conservative friction angles for humified peat based on literature review	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)

		(only 20° used in analysis)	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 (downsampled from 0.5m LiDAR data)
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. 3,730 facets were considered in the analysis, with an average area of c. 3,480 m^2 (or an average footprint of c. 58 m x 58 m, consistent with 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 Figure 8.4.2 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.

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.	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 8.4.7 shows the distribution of slope angle scores across the site. Much of the site on the middle and lower slopes receives the highest score.

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 8.4.5 and reflect the peat depth ranges most frequently associated with peat slides (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 8.4.7. Much of the site lacks peat entirely and therefore has the lowest score, however the areas with peat generally fall within the most commonly cited depth range for peat slides and therefore have the highest score.

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 clay substrates and/or iron pans	3

Granular clay or clay dominated alluvium	Failures are more frequently associated with substrates with some clay 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 at 15 locations indicated a stiff clay over bedrock, and accordingly, the full site is scored as 2 (Figure 8.4.7).

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 / intermittent subsurface drainage pathways	Failures generally occur on planar slopes, and are often reported in areas of piping	3
Flush / Diffuse surface drainage	Peat slides are often reported in association with areas of flushed peat or diffuse drainage	3
Planar slopes in peat (no other features)	Failures generally occur on planar slopes rather than dissected or undulating slopes	2
Planar slopes in soil	Only peaty-debris slides can occur in areas of organic soil	1
Minor gullying / erosion	Failures are rarely reported in areas with gullying or bare peat	1
Afforested / deforested peatland	Considered within Forestry (F), see below	0

Table 4-5 Peat geomorphology classes, association with instability and scores

Figure 8.4.7 shows the geomorphological classes from Figure 8.4.4 re-coloured to correspond with Table 4-5. Much of the site comprises planar slopes, although steep valley sides and diffuse drainage / intermittent subsurface drainage pathways are observed at valley heads and have higher scores.

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). Buffers are shown on Figure 8.4.7.

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	3
Convex Slope	Peat slides are often reported on or above convex slopes	2
Concave Slope	Peat failures are occasionally reported in association with concave slopes	1

Table 4-7 Slope curvature classes, association with instability and scores

The resampled 5 m digital terrain model and OS contours were used to identify areas of noticeable slope convexity across the site (Figure 8.4.7). Concavities were generally absent. Axes of convexity (running along the contour) were assigned a 50 m buffer to produce 100 m (upslope to downslope) convexity zones and these were assigned scores in accordance with Table 4-7 above.

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

None of the site is afforested and therefore the full site receives a zero score for this factor (see Figure 8.4.7).

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 paragraph 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

Aside from grazing, which is likely to have a minimal effect, burning is the primary land use on site. Although cracking was not particularly evident in the burned areas during walkover, a conservative score of 1 has been applied to all of the areas that have been subject to recent enough burning for burn patterns to be visible on satellite imagery. Areas upslope of very small scale cutting in the north of the site and above quarries in the central valley have also been scored in line with Table 4-9 (see Figure 8.4.7).

4.3.10. Generation of Slope Facets

The eight contributory factor layers shown on Figure 8.4.7 were combined in ArcMap to produce approximately 3,733 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 8.4.8 shows the outputs of the landslide susceptibility approach for peat slides. The results indicate that the majority of the site has a 'Low' or 'Very Low' likelihood of failure, with localised areas of Moderate likelihood (generally concentrated around valley heads, which are generally avoided by infrastructure.

4.3.12. Combined Landslide Likelihood

Figure 8.4.8 shows in purple any proposed areas of infrastructure of greater than 25 m in length intersecting with areas of moderate or higher landslide susceptibility (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. In order 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. Two infrastructure locations overlap with areas of “Moderate” landslide likelihood.

		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

Section 5 of this report describes the consequence assessment and risk calculation for all areas where infrastructure intersects “Moderate” likelihood of a peat landslide.

5. ASSESSMENT OF CONSEQUENCE AND RISK

5.1. Introduction

In order 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 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 numerous watercourses between the spur ridges that fall towards the Dye valley. The Dye Water is considered of high sensitivity for water quality due to surface water abstractions, reservoir supply and being part of the River Tweed SAC (which begins where Kersons Cleugh joins the river from the northern side of the valley. While Kersons Cleugh and the other minor watercourses are not designated and are too small to be classified for water quality, they directly feed the Dye Water and are considered as high sensitivity receptors in this assessment (consequence score of 4). The main surface water abstraction location that might be affected by landslide debris is a 50 m^3 / day abstraction point just downstream of Kersons Cleugh (CAR/R/1101731, see Chapter 8). Other abstraction points are either well downstream within the Dye Water or upstream of potential source zones within the Fallago Rig site.

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, and therefore a consequence score of 3 is assigned for all open habitats in peatland within the Proposed Development site (Table 5-1).

Receptor and type	Consequence	Score	Justification for Consequence Score
Watercourses (water quality)	Short term increase in sediment load affecting water quality at offtakes	4	Short term effects on water quality and minor remedial works may be required, however medium to long-term effects are unlikely
Terrestrial habitats	Short to medium term loss of vegetation cover, disruption of peat hydrology, carbon release	3	Habitats in peat areas noted to be dry modified bog (with minimal *Sphagnum*), long term effects unlikely following revegetation
Wind farm infrastructure (Project)	Damage to infrastructure, injury to site personnel, possible loss of life	5	Loss of life, though very unlikely, is a severe consequence; financial implications of damage and re-work are less significant

Table 5-1 Receptors considered in the consequence analysis

5.2.3. Infrastructure

The Proposed Development site is primarily used for agriculture with related buildings and roads in the valley floor below. The operational Fallago Rig wind farm overhead lines (OHL) pass by the northwest side of the Site boundary.

The infrastructure that would be most affected in the event of a peat landslide would be the Proposed Development infrastructure. These effects would be most likely during construction, at which time personnel would be using the access track network or be present at infrastructure locations for long periods. While commercial losses would be important to the Applicant, loss of life / injury would be of greater concern, and a consequence score of 5 is assigned for any infrastructure locations subject to potential peat landslides (Table 5-1). However, risks to life can be mitigated through safe systems of working. These infrastructure risks are not considered to be ‘environmental’ risks and are not explicitly considered in the consequence assessment below.

5.3. Consequences

5.3.1. Overview

A consequence assessment has been undertaken by determining the potential for landslides sourced at infrastructure locations with a Moderate natural likelihood of peat instability to impact the receptors identified above. For 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.

In order 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 source zone area is either footprint of hardstandings or non-linear infrastructure or where an access track is the source, the track length multiplied by a typical landslide downslope length of 25 m.

Figure 8.4.8 shows in purple all infrastructure locations that overlap with moderate likelihoods, based on the landslide likelihood scores described in Section 4.

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. At this site, the minor tributaries to Dye Water are relatively steep and therefore there is relatively high connectivity between the upper parts of the site and the river valley.

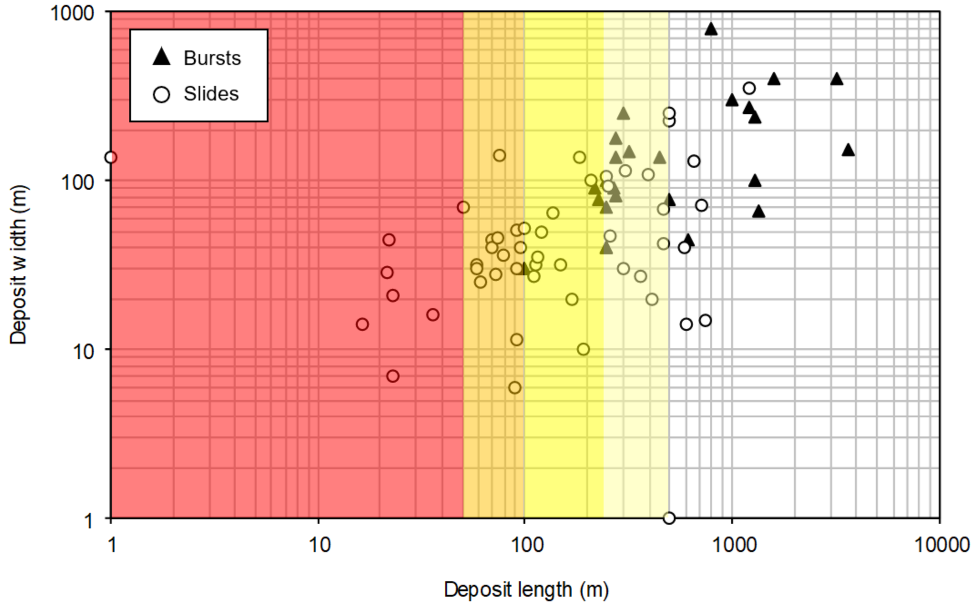

Plate 5.1 Runout distances for published peat landslides (after Mills, 2002), colours on the plot correspond to runout pathway zones on Figure 8.4.9

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. At the Proposed Development site, slopes steepen towards the valley floor (i.e. they are convex) and the runout distances shown on Plate 5.1 are considered likely to apply.

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 5.2).

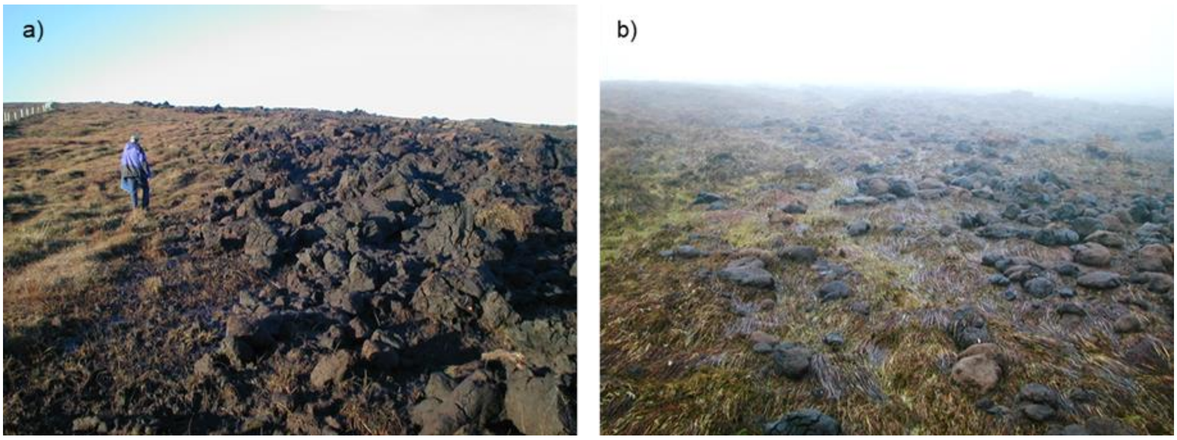

Plate 5.2 Examples of landslide runout (Dooncarton, Co. Mayo): a) blocky debris mid-slope, b) abraded and rolled blocks in lower slope

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 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 runout zone adjoining a watercourse, then it is judged that the runout will stall prior to reaching it or be negligible in volume on entry and there will be no significant impact on that watercourse (even if a landslide occurs).

Plate 5.3 shows a schematic of the full runout approach to assessing consequences.

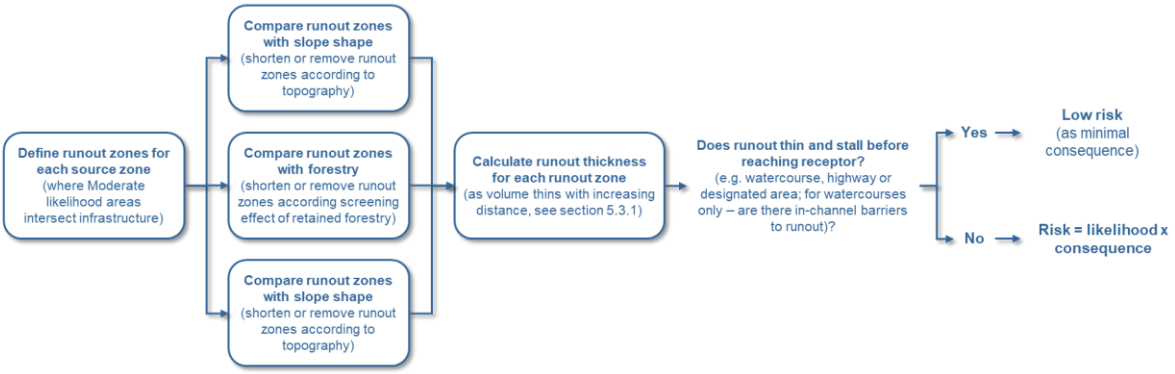

Plate 5.3 Runout approach to assessing consequences

5.3.5. Results of runout analysis

Of the 2 source zones, both have the potential for runout to reach named watercourses (see Figure 8.4.9):

- **Source zone 1 (floating access track east of Turbine 14):** downslope end of 250-500 m runout zone overlaps with headwaters of Foul Cleugh.
- **Source zone 2 (cut and fill access track to Turbine 4):** the downslope end of the 100-250 m runout zone enters Marlin Grain which feeds Kersons Cleugh and ultimately (c. 1.4 km downstream) the Dye Water.

Foul Cleugh joins the Dye Water c. 200 m upstream of a rock weir which is likely to hold back any minor residual debris remaining after its passage down 1.4 km of valleyside stream. None of the surface water abstraction points are likely to be affected. Kersons Cleugh joins the Dye Water just upstream of an abstraction point.

In both cases, the runout thickness in the runout zones overlapping with watercourses thin to <0.2 m, and this implies that runout will stall within these zones, with either no entry of material to the watercourses or negligible volumes. For Foul Cleugh, runout is indicated to be c. 0.04 m thick and for Marlin Grain c. 0.07 m thick. This is because the source zones are relatively small with source volumes < 1,000 m^3, this in turn a result of the relatively thin peat in both locations.

5.4. Calculated Risk

Risk levels have been calculated as a product of likelihood and consequence and are shown on Figure 8.4.10 for each runout pathway. Each runout zone is colour coded to match the risk rankings shown on Plate 5.1. Runout zones which are 'supply limited' (i.e. runout thins and stalls) are shown with hatching.

For each zone, the score for the most sensitive environmental receptor has been chosen for the risk calculation (i.e. a conservative approach). For Dunside, these receptors are watercourses.

Figure 8.4.10 indicates that risks are calculated to be “Low” for the two runout zones. There are no “Medium” or “High” calculated risks. Based on these calculated risks site-wide good practice measures should be sufficient to manage and mitigate any construction induced instability. This is considered in the next section.

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”, 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.
- Undertake site specific stability analysis for all areas of peat storage (if on sloping ground) to ensure the likelihood of destabilisation of underlying peat is minimised.
- Avoid storing peat on slope gradients >3° and preferably store on ground with neutral slopes and natural downslope barriers to peat movement.
- Monitor effects of wetting / re-wetting stored peat on surrounding peat areas, and prevent water build up on the upslope side of peat mounds.
- Undertake regular monitoring of emplaced peat in restoration areas to identify evidence of creep or pressure on retaining structures (dams and berms).
- 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 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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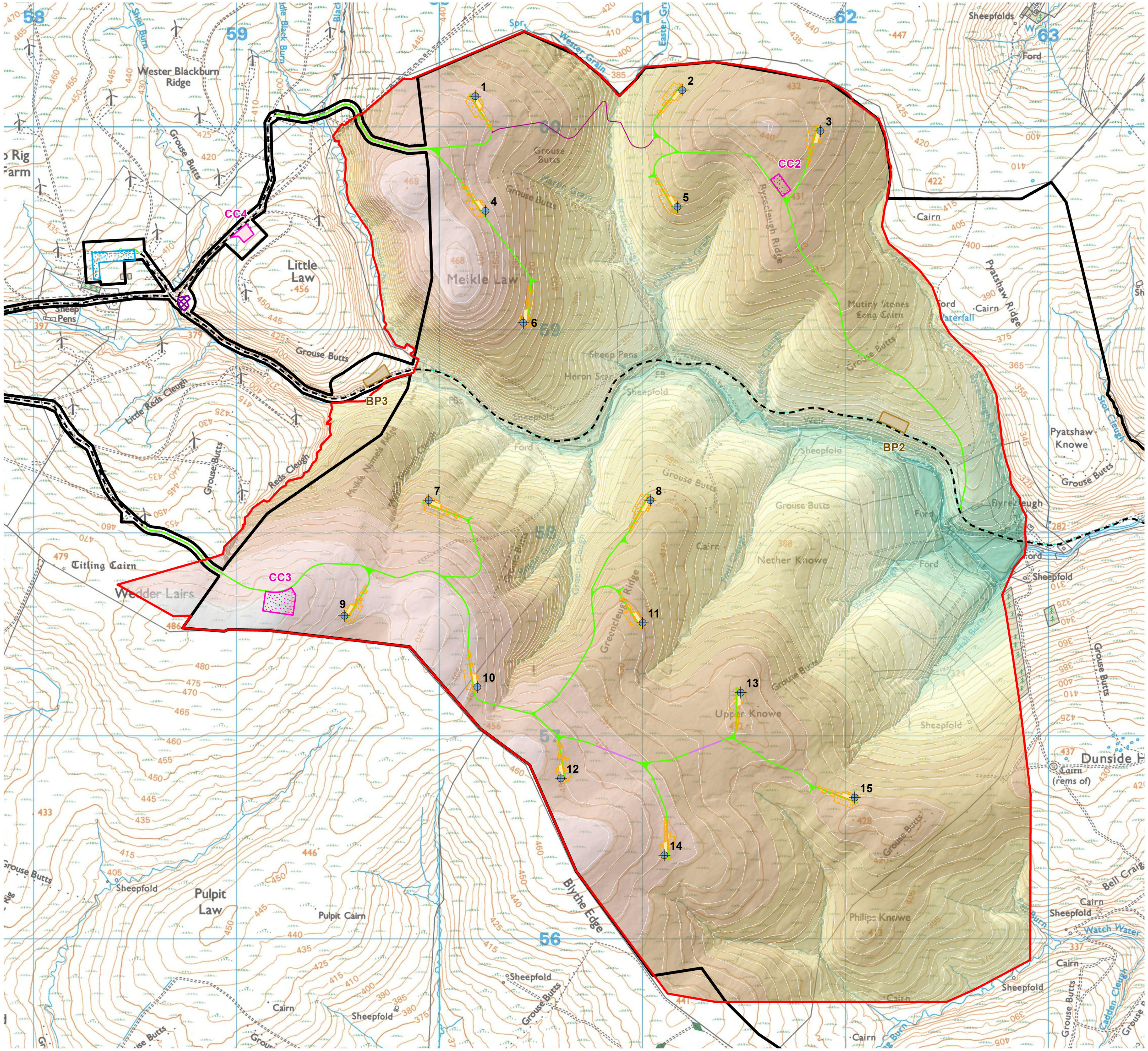
Figure 8.4.1 Elevation

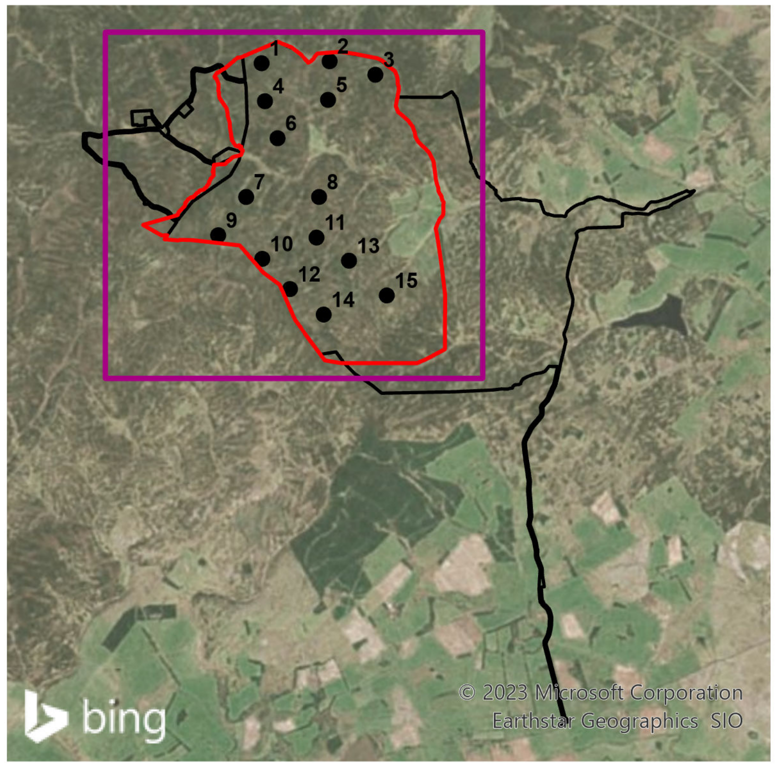


Legend

- Turbine
- PLHRA Extent
- Site Boundary
- Battery storage
- Construction compound
- Existing construction compound
- Substation extension
- Borrow pit
- Temporary hardstanding
- Permanent hardstanding
- Existing track
- Proposed existing track upgrade
- Proposed light vehicle track (3m wide)
- Proposed new track (floating)
- Proposed new track

Elevation (m)

- <= 220
- 221 - 240
- 241 - 260
- 261 - 280
- 281 - 300
- 301 - 320
- 321 - 340
- 341 - 360
- 361 - 380
- 381 - 400
- 401 - 420
- 421 - 440
- 441 - 460
- 461 - 480
- 481 - 500



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Map scale 1:20,000 @ A3

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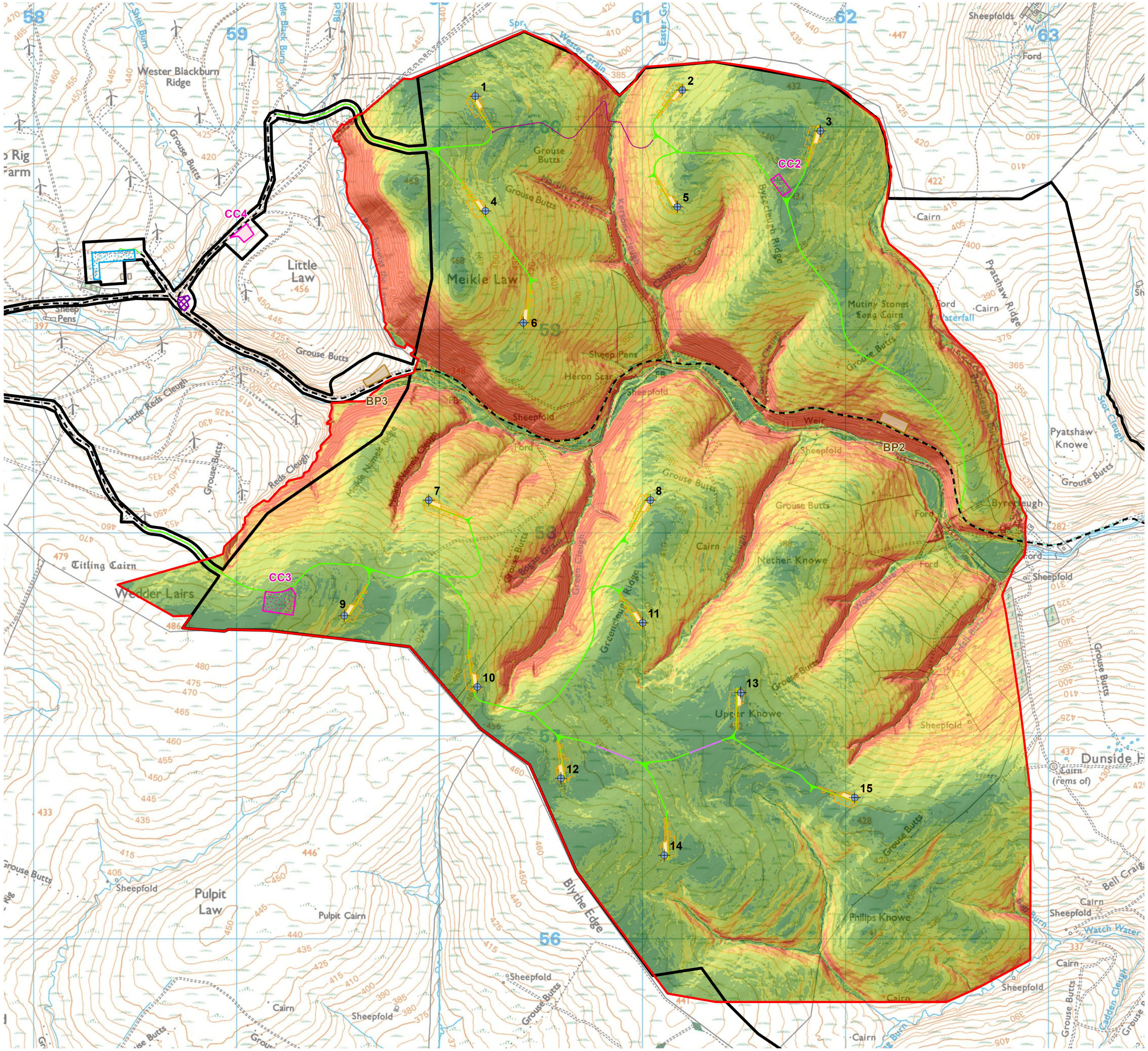
Figure 8.4.2 Slope



Legend

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- Proposed new track (floating)
- Proposed new track

Slope (degrees)

- 0.0 - 2.5
- 2.5 - 5.0
- 5.0- 7.5
- 7.5 - 10.0
- 10.0- 15.0
- > 15.0

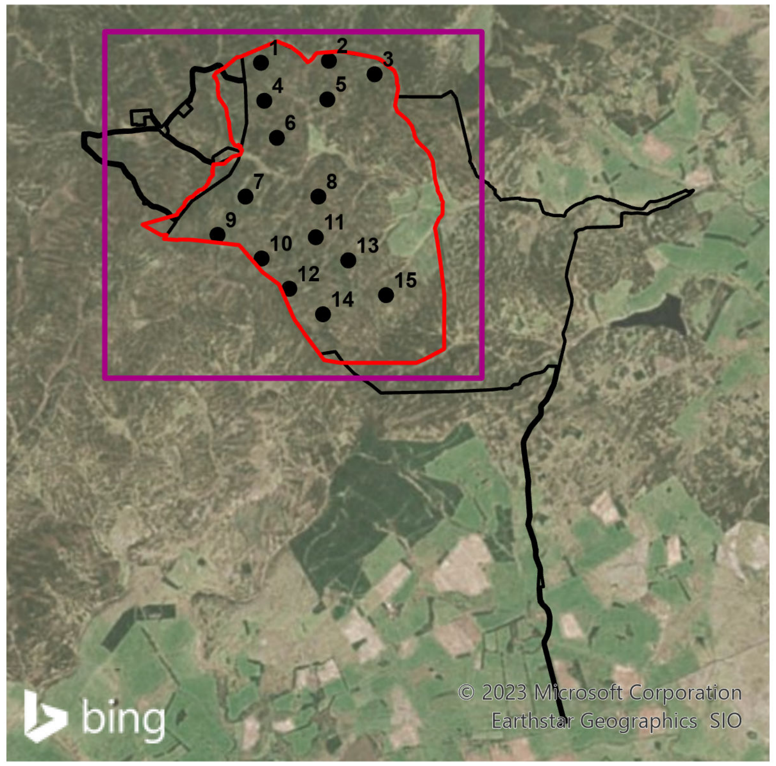

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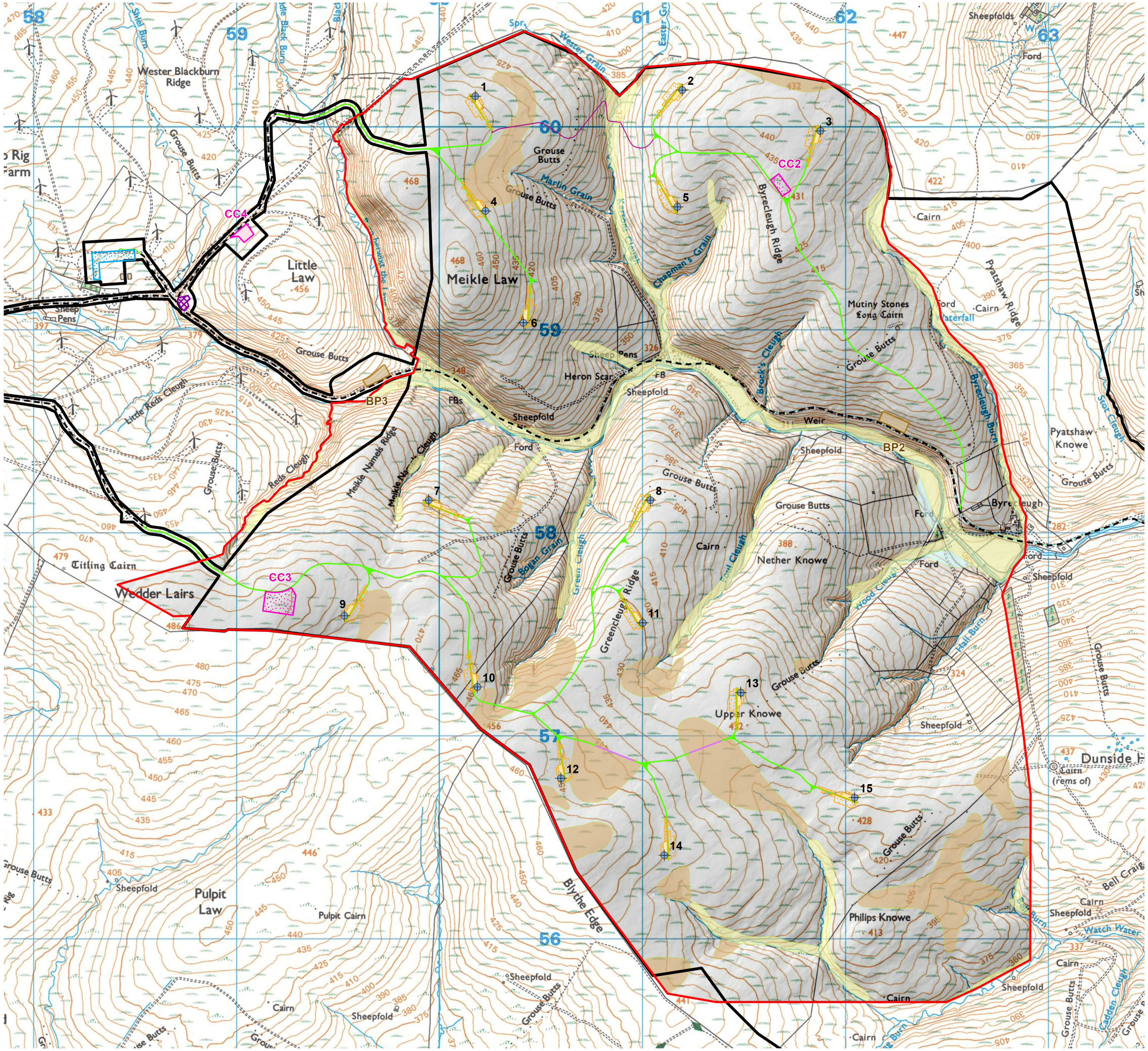
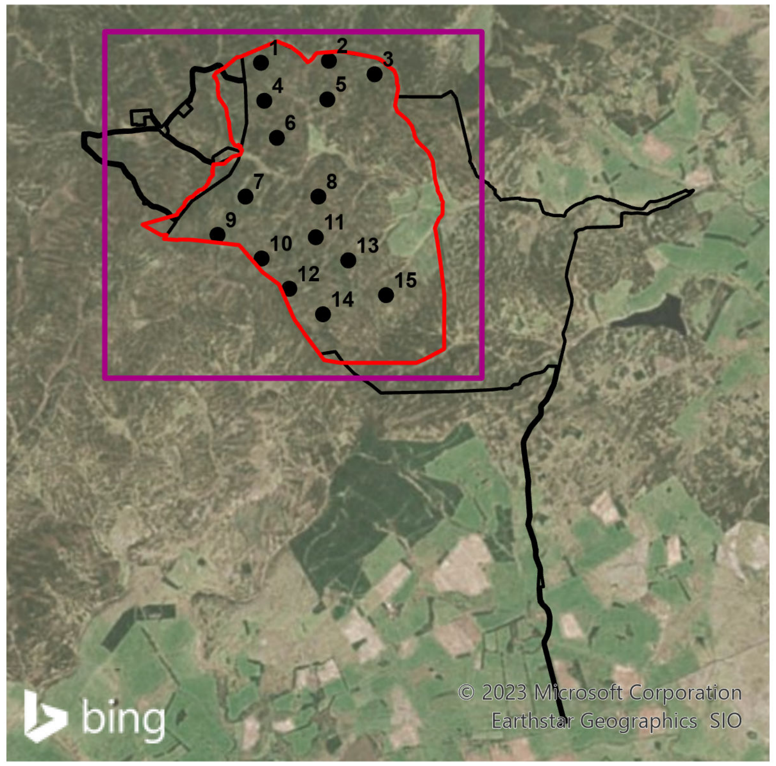
Figure 8.4.3 Geology





Legend

- Turbine
- PLHRA Extent
- Site Boundary
- Battery storage
- Construction compound
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- Substation extension
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- Permanent hardstanding
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- Proposed existing track upgrade
- Proposed light vehicle track (3m wide)
- Proposed new track (floating)
- Proposed new track

Superficial Geology

- Alluvium - Silt, sand and gravel
- No Deposits
- Peat
- Till, Devensian - Diamicton

0 0.5 1 km

Map scale 1:20,000 @ A3

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Figure 8.4.4 Geomorphology, Hydrology and Land Use

Legend

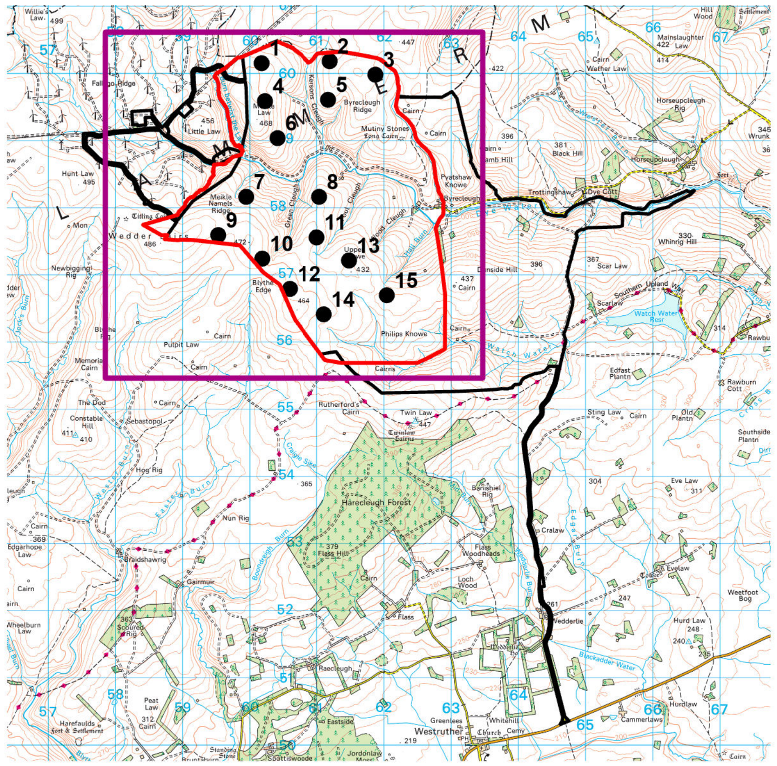
- Turbine
- PLHRA Extent
- Site Boundary
- Battery storage
- Construction compound
- Existing construction compound
- Substation extension
- Borrow pit
- Temporary hardstanding
- Permanent hardstanding
- Existing track
- Proposed existing track upgrade
- Proposed light vehicle track (3m wide)
- Proposed new track (floating)
- Proposed new track
- Morphology

Hydrology

- Drain
- Watercourse

Terrain/Geomorphology

- Valley floor
- Diffuse surface drainage
- Minor gullying / erosion
- Cuttings
- Quarry
- Intermittent subsurface drainage path
- Gentle planar summits (soil)
- Moderate slopes (5-15 deg) (soil)
- Gentle planar summits (in peat)
- Moderate slopes (5-15 deg) (in peat)
- Steep valley sides (>15 deg)



0 0.5 1 km

Map scale 1:20,000 @ A3

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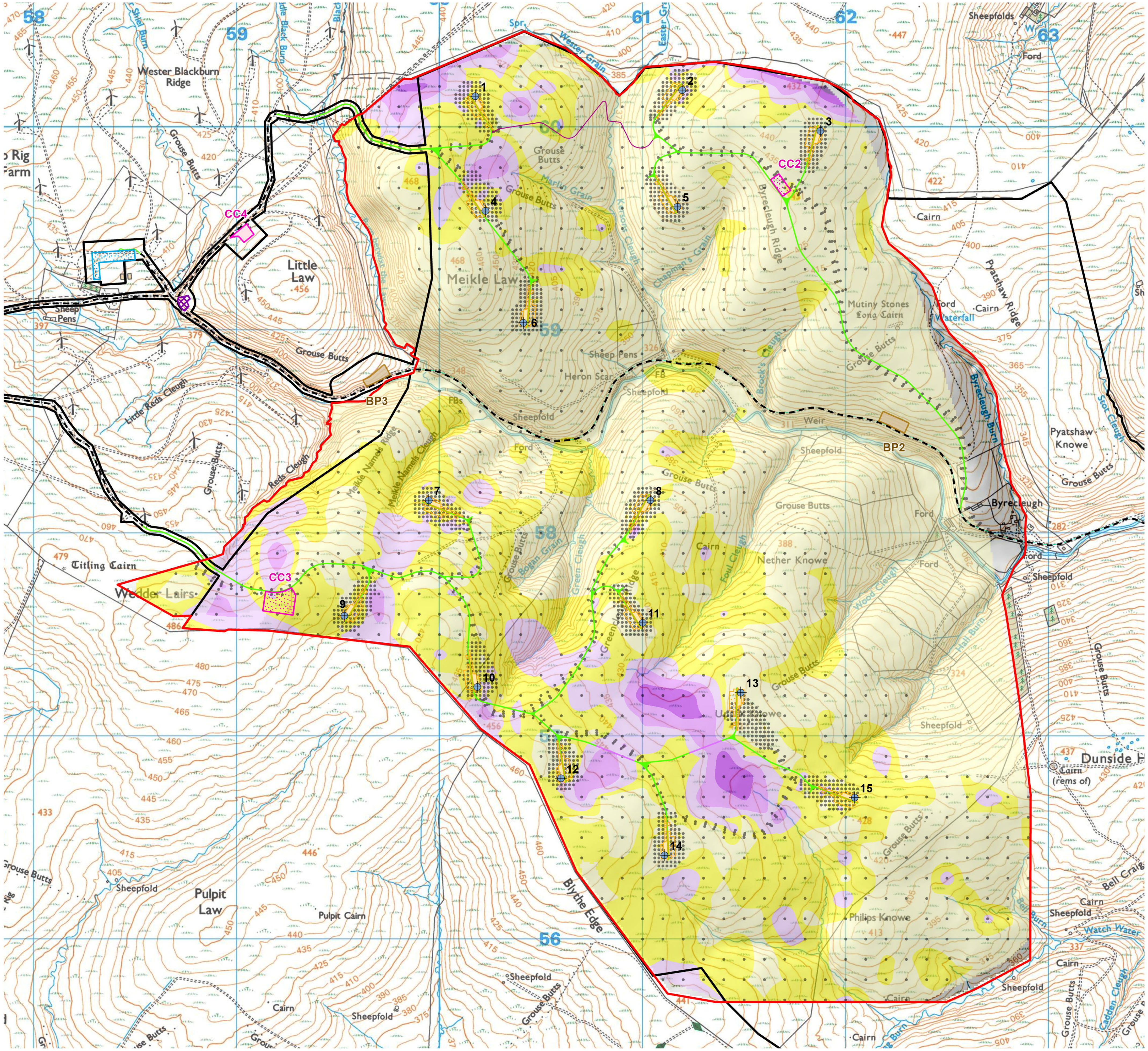
Figure 8.4.5 Peat Depth



Legend

- Turbine
- PLHRA Extent
- Site Boundary
- Battery storage
- Construction compound
- Existing construction compound
- Substation extension
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- Proposed new track (floating)
- Proposed new track

Probe Locations (All)

Peat Depth (cm)

- <= 30
- 31 - 50
- 51 - 100
- 101 - 200
- 201 - 300
- 301 - 400
- 401 - 500

Carbon and Peatland (2016) Map

- Class 1
- Class 2
- Class 3
- Class 4
- Class 5
- Mineral Soil
- Unknown Soil
- Non Soil

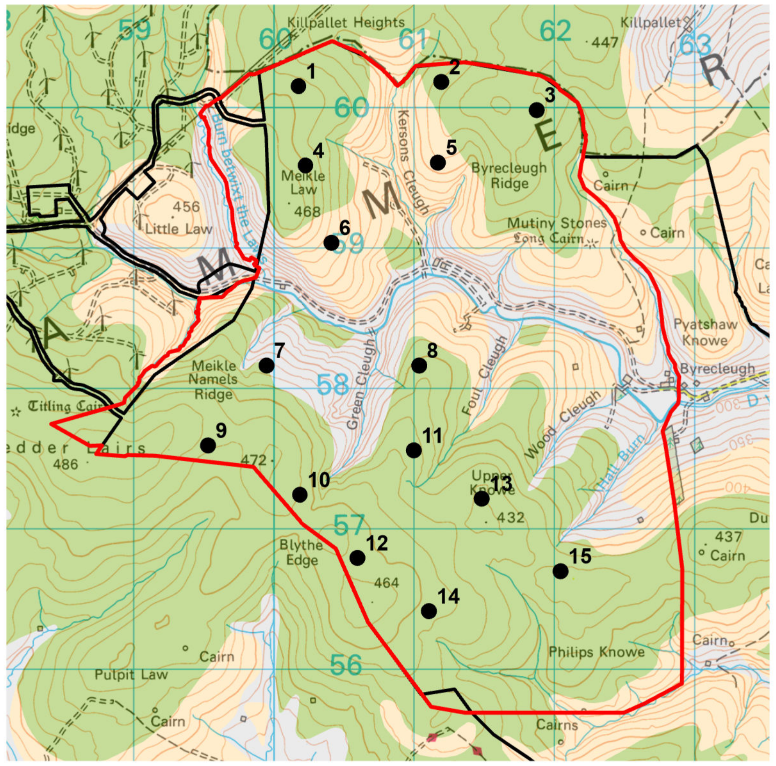

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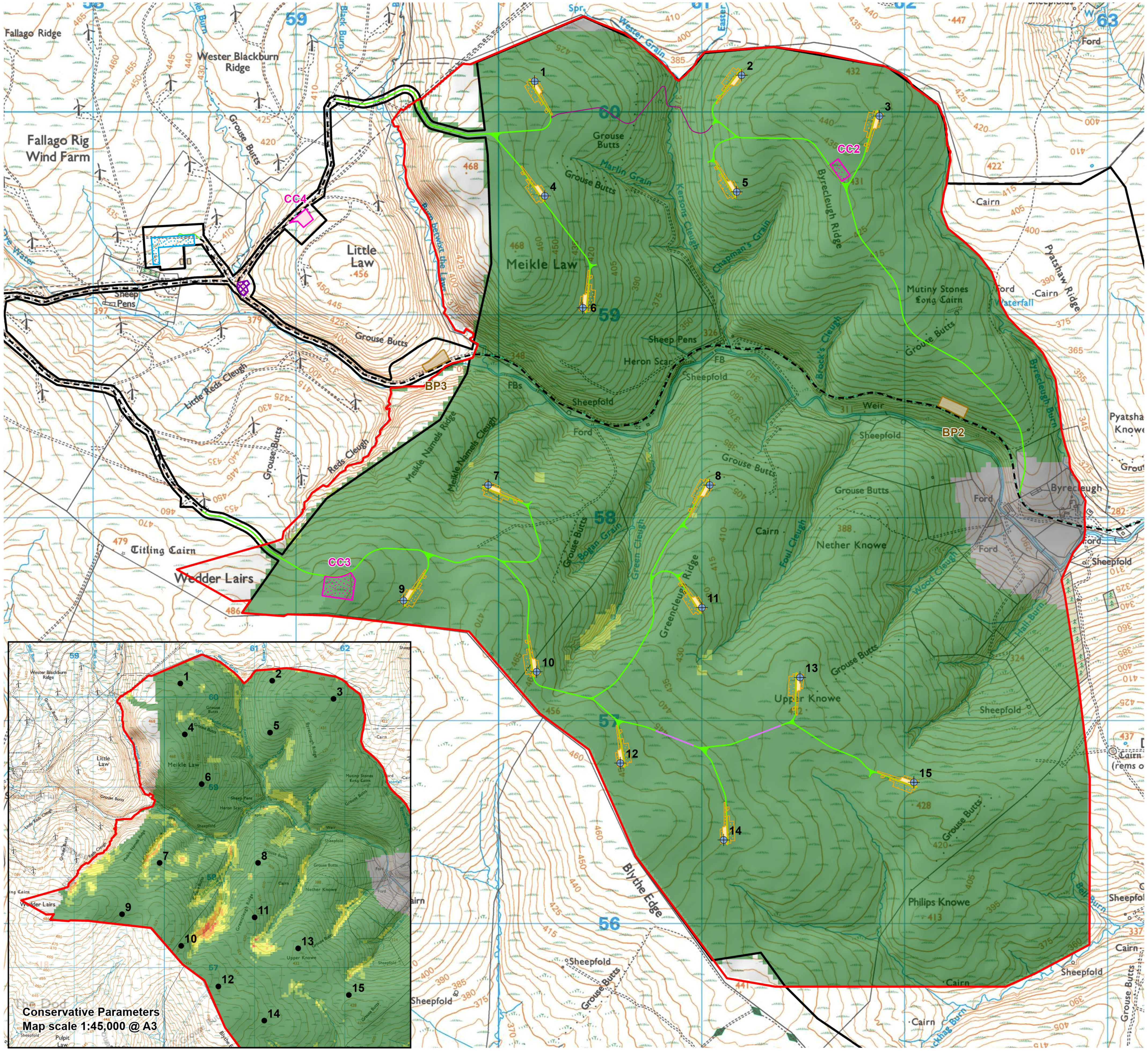
Figure 8.4.6 Factor of Safety (Best Estimate Parameters)



Legend

- Turbine
- PLHRA Extent
- Site Boundary
- Battery storage
- Construction compound
- Existing construction compound
- Substation extension
- Borrow pit
- Temporary hardstanding
- Permanent hardstanding
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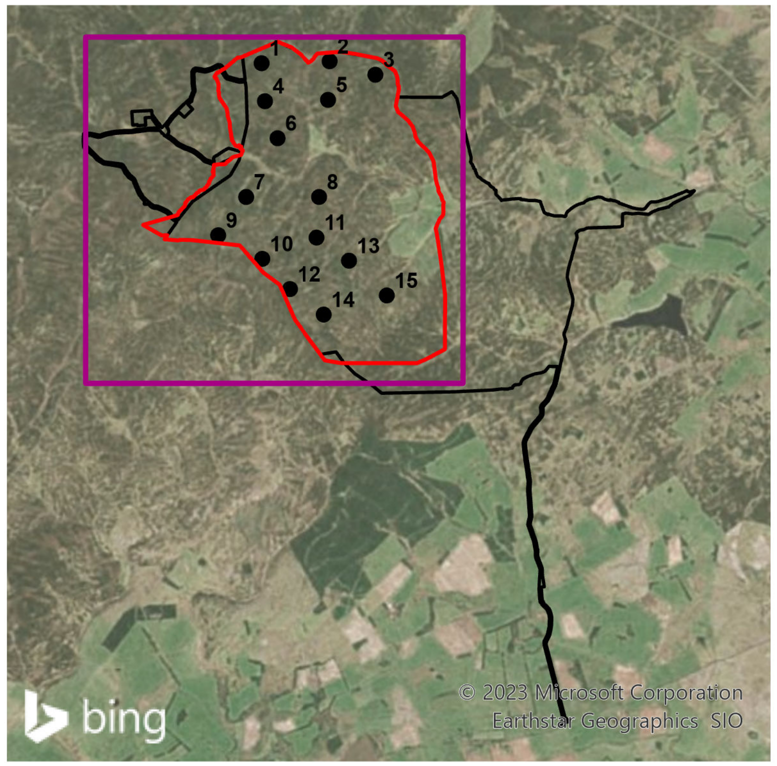
- Proposed existing track upgrade
- Proposed light vehicle track (3m wide)
- Proposed new track (floating)
- Proposed new track

Factor of Safety (Best Estimate)

- < 1.00 "Unstable" (None Calculated)
- 1.01 - 1.40 "Marginally Stable"
- 1.41 - 2.00 "Stable"
- 2.01 - 3.00 "Stable"
- > 3.01 "Stable"
- No Calculation



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Map scale 1:20,000 @ A3

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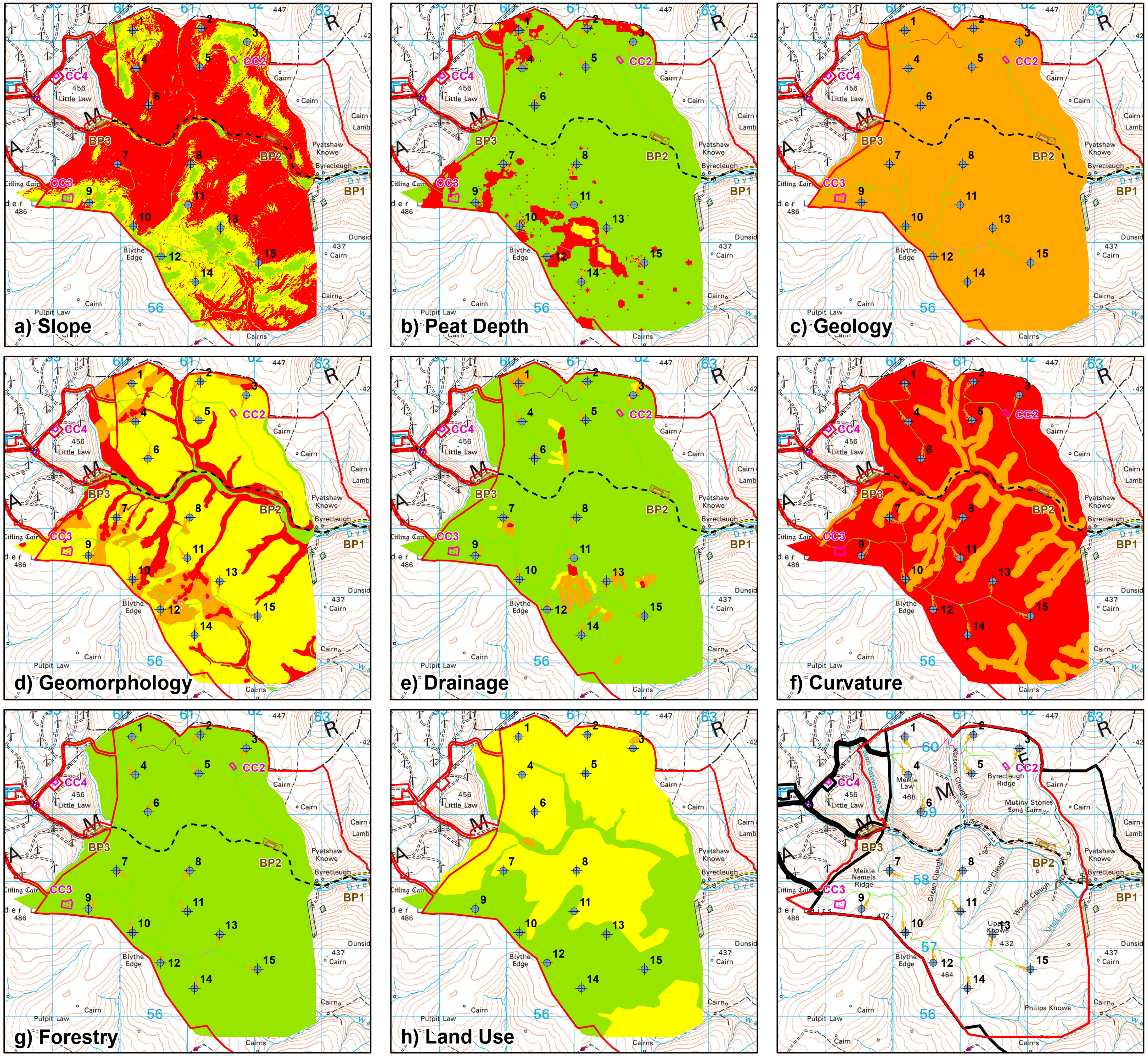
Figure 8.4.7 Contributory Scores



Legend

- Turbine
- PLHRA Extent
- Site Boundary
- Battery storage
- Construction compound
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- Substation extension
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- Permanent hardstanding
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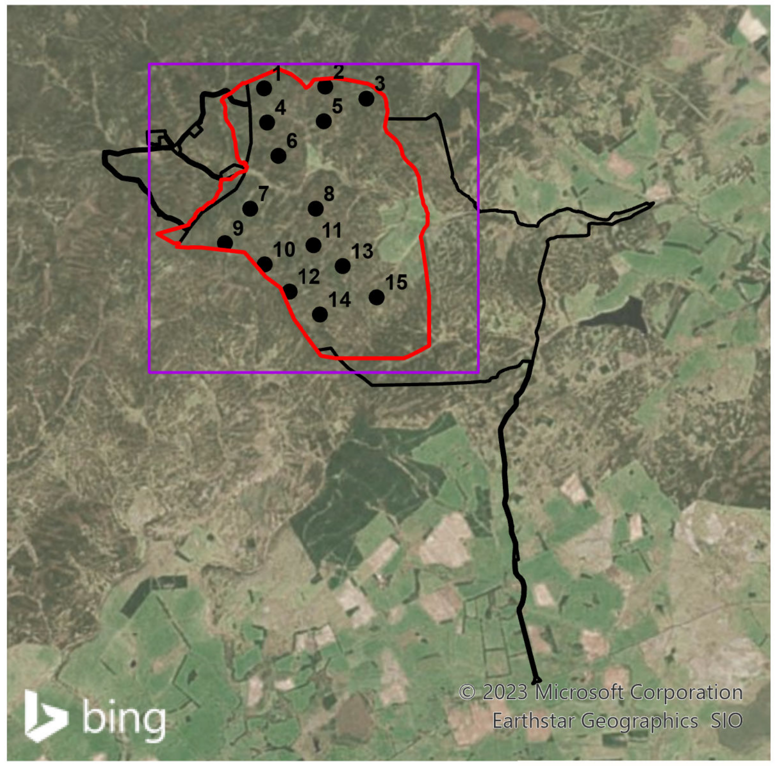
- Proposed new track (floating)
- Proposed new track

Contributory Scores

- 0
- 1
- 2
- 3



0 0.5 1 km

Map scale 1:60,000 @ A3

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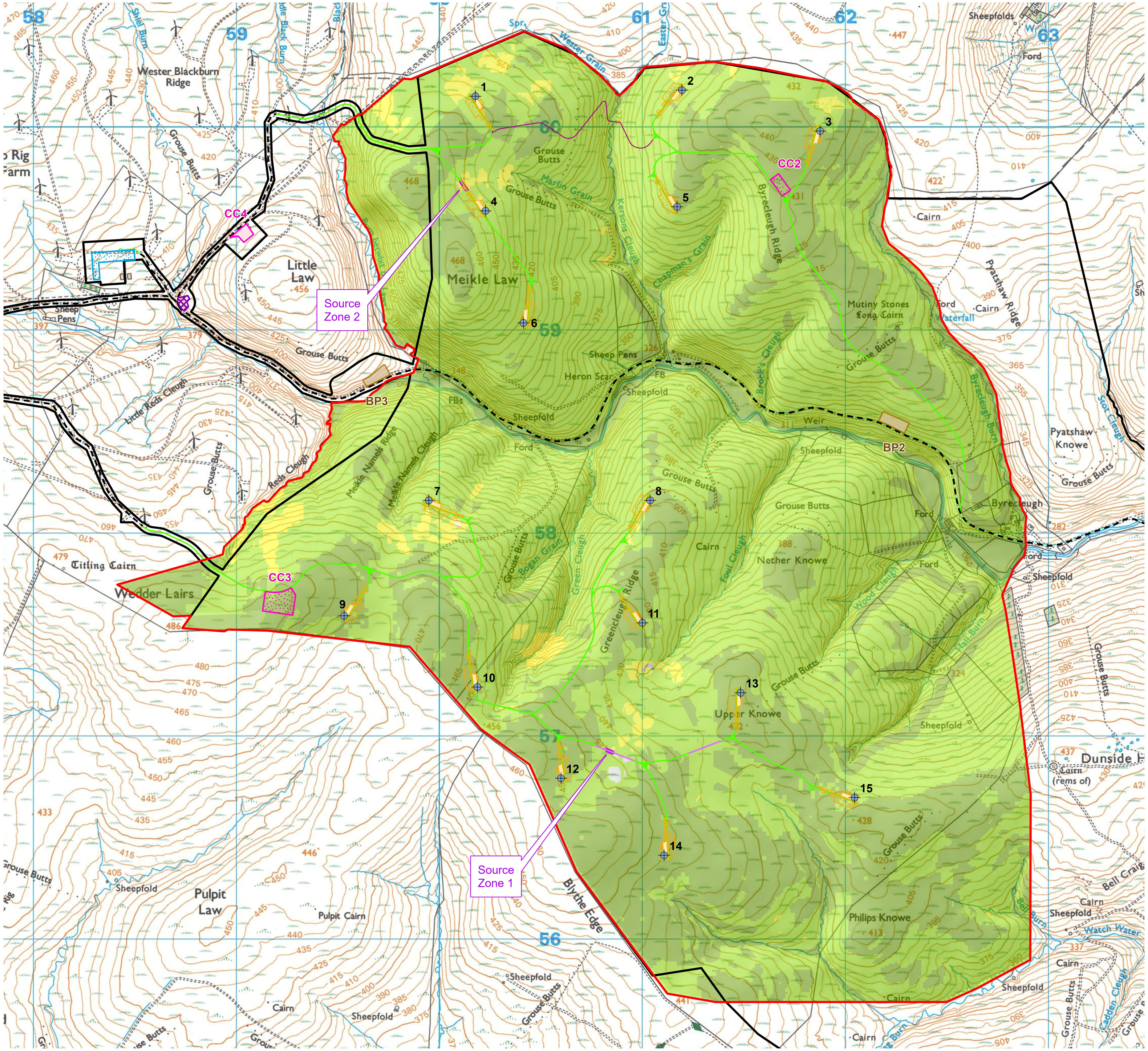
Figure 8.4.8 Peat Landslide Likelihood



Legend

- Turbine
- PLHRA Extent
- Site Boundary
- Battery storage
- Construction compound
- Existing construction compound
- Substation extension
- Borrow pit
- Temporary hardstanding
- Permanent hardstanding
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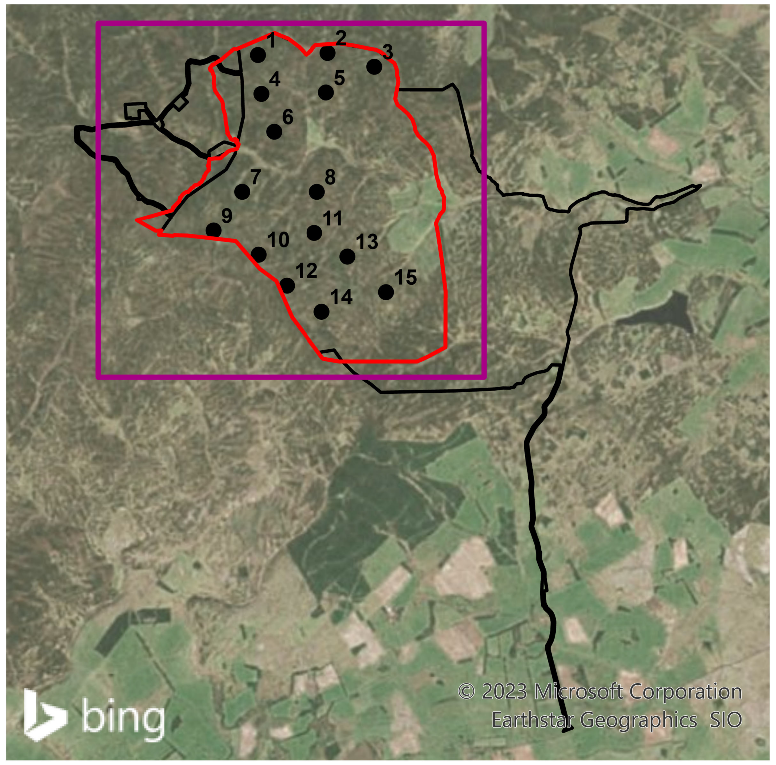
- Proposed existing track upgrade
- Proposed light vehicle track (3m wide)
- Proposed new track (floating)
- Proposed new track

Landslide Susceptibility

- Very Low
- Low
- Moderate
- High (None calculated)
- Very High (None calculated)
- Source Zones



0 0.5 1 km

Map scale 1:20,000 @ A3

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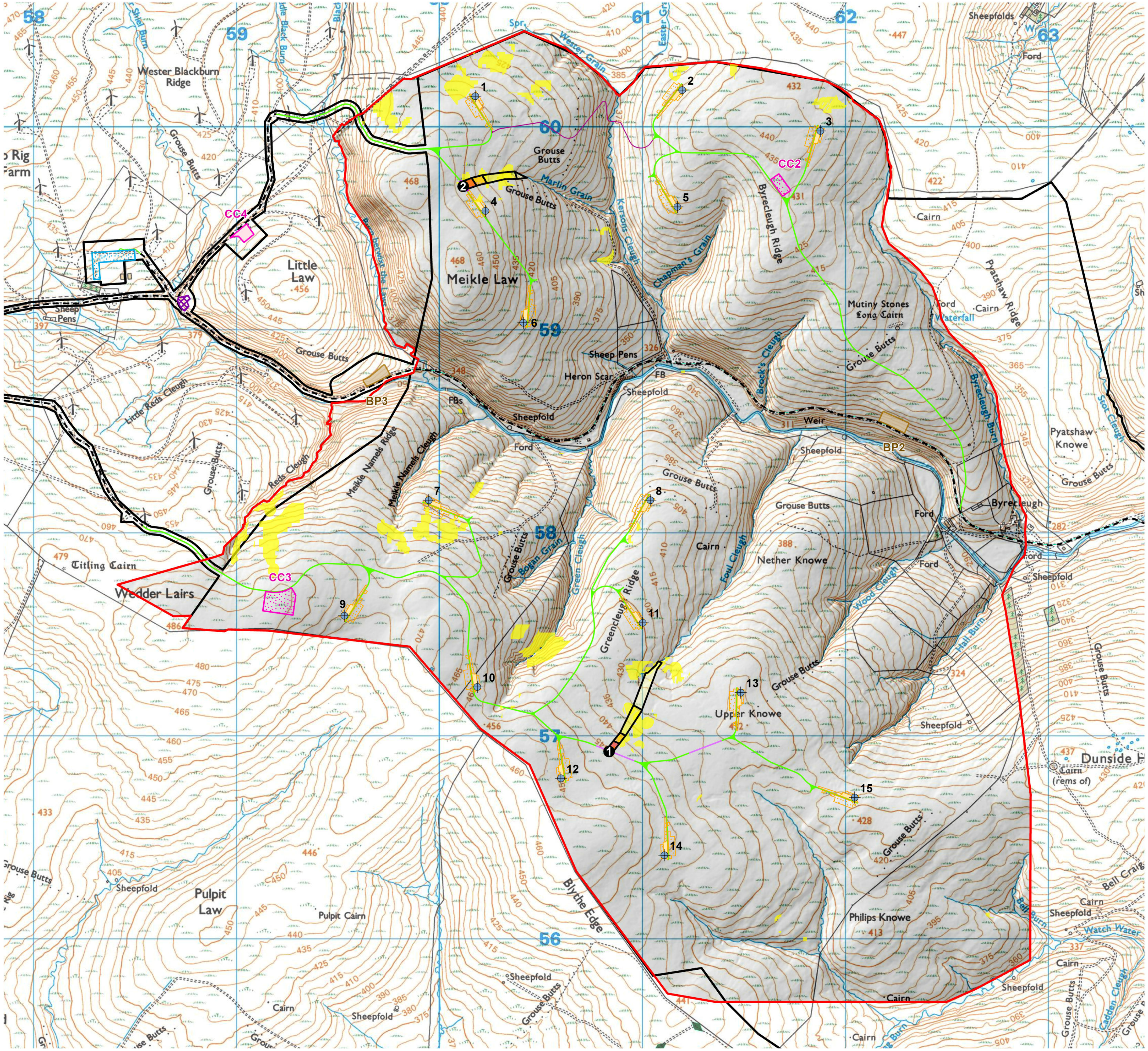
Figure 8.4.9 Source and Runout Zones



Legend

- Turbine
- PLHRA Extent
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- Construction compound
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- Permanent hardstanding
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- Proposed light vehicle track (3m wide)
- Proposed new track (floating)
- Proposed new track

Landslide Susceptibility Score

- Moderate

Factor of Safety (Best Estimate)

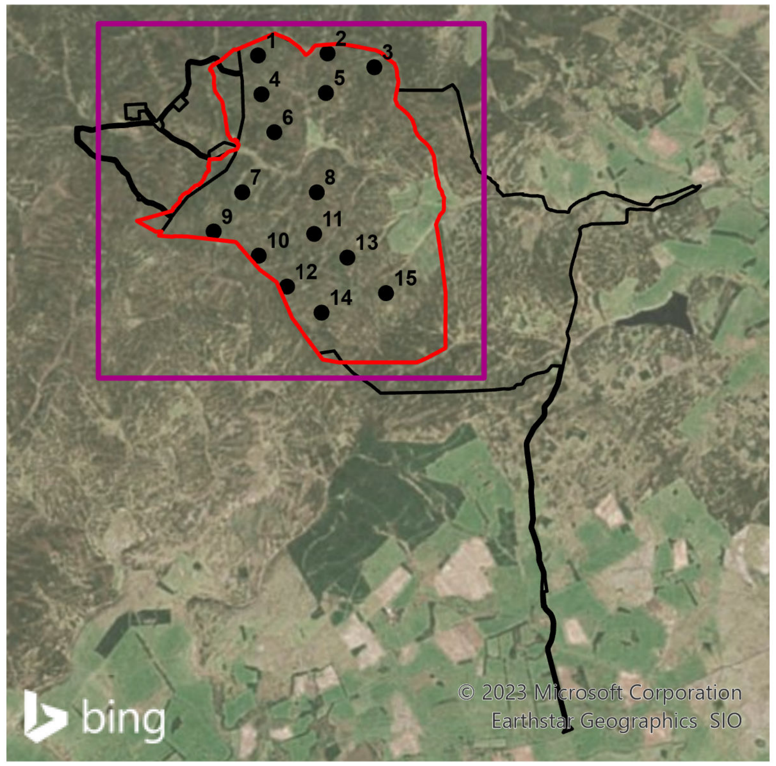
- < 1.0 (Unstable)
- 1.0 - 1.4 (Marginally Stable)
- None Calculated

Source Zones

- Source Zone ID
- Source Zones

Runout Zones

- 50
- 100
- 250
- 500



0 0.5 1 km

Map scale 1:20,000 @ A3

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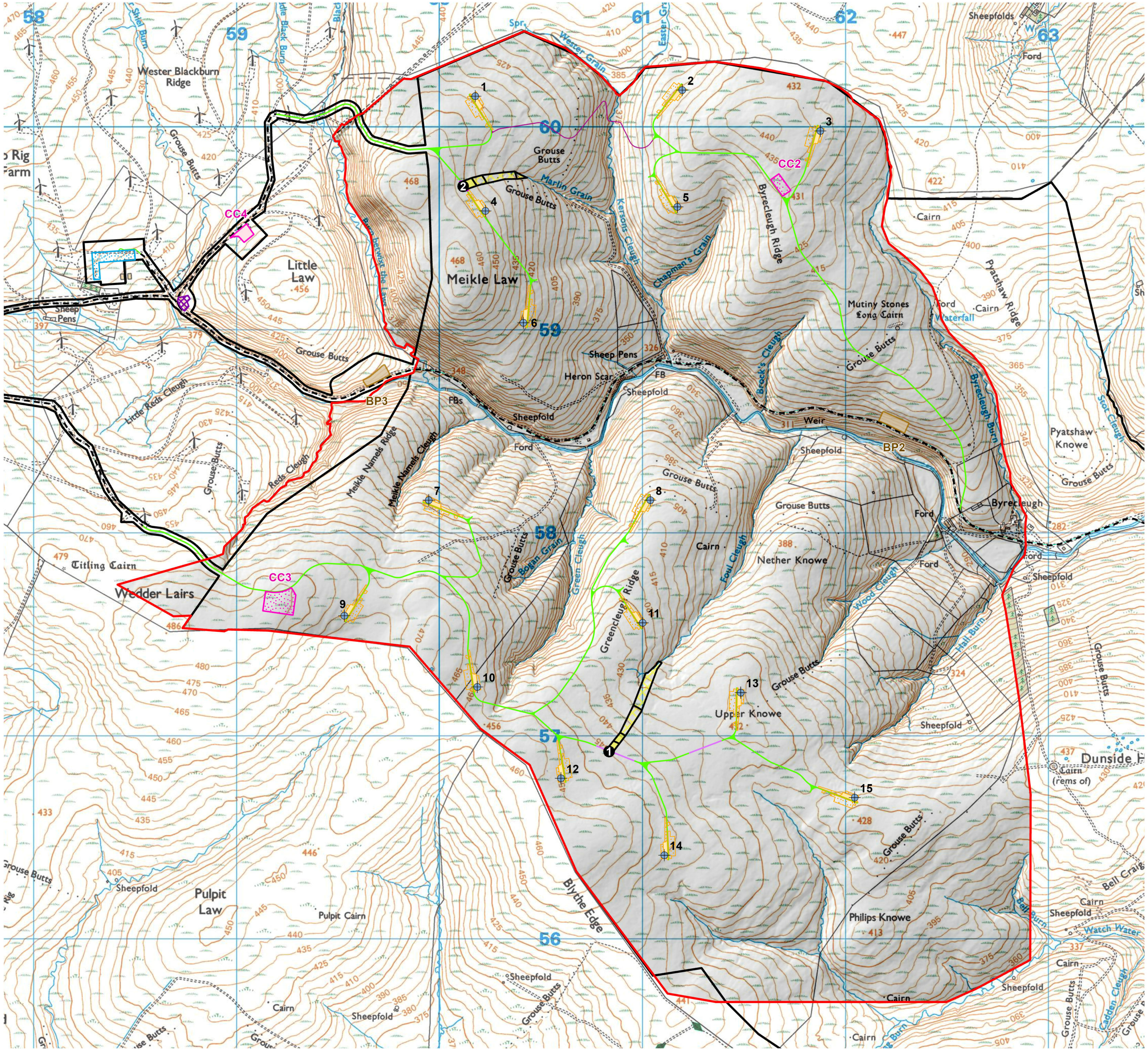
Figure 8.4.10 Calculated Risk



Legend

- Turbine
- PLHRA Extent
- Site Boundary
- Battery storage
- Construction compound
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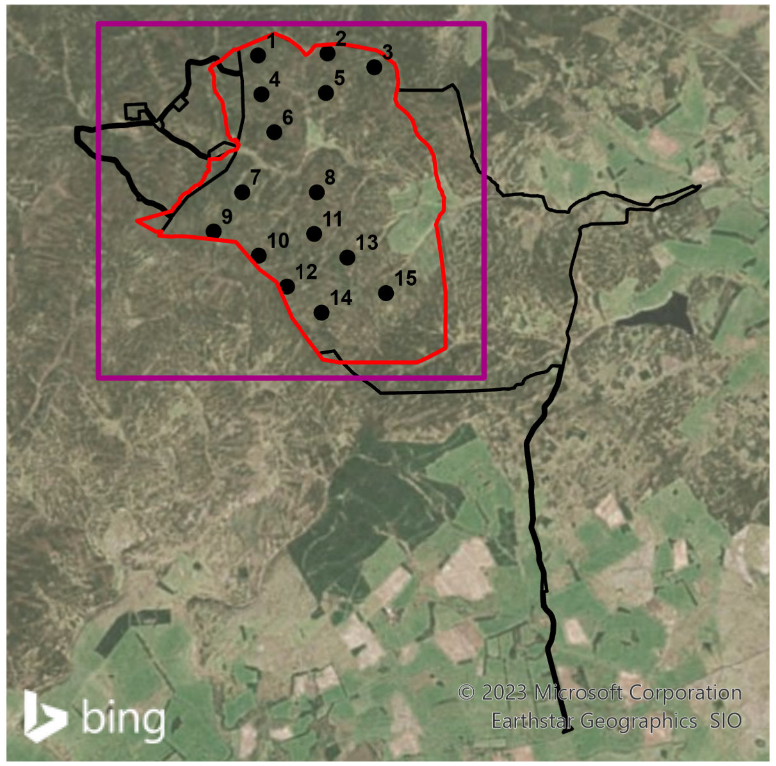
- Substation extension
- Borrow pit
- Temporary hardstanding
- Permanent hardstanding
- Existing track
- Proposed existing track upgrade
- Proposed light vehicle track (3m wide)
- Proposed new track (floating)
- Proposed new track

Source Zones

- Source Zone ID
- Source Zones

Calculated Risk

- High
- Medium
- Low
- Low - runout <0.2m
- Negligible



0 0.5 1 km

Map scale 1:20,000 @ A3

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