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ASSESSMENT OF MAIN CONTRIBUTING FACTORS LEADING TO THREE MAJOR PEATLAND FAILURES IN LEITRIM, KERRY AND DONEGAL

LITERATURE REVIEW OF CONDITIONING AND TRIGGERING FACTORS IN PEAT FAILURES

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Abstract: Task 1 of the project involves a literature review to determine the documented contributory factors in peat failures.

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1. Introduction

1.1 Fehily Timoney and Company

Fehily Timoney and Company (FT) is an Irish engineering, environmental science, and planning consultancy with offices in Cork, Dublin and Carlow. The practice was established in 1990 and currently has c.95 members of staff, including engineers, scientists, planners and technical support staff. We deliver projects in Ireland and internationally in our core competency areas of Waste Management, Environment and Energy, Civils Infrastructure, Planning and GIS and Data Management.

FT have been involved in over 100 wind farm developments in both Ireland and the UK at various stages of development i.e. preliminary feasibility, planning, design, construction and operational stage and have established themselves as one of the leading engineering consultancies in peat stability assessment, geohazard mapping in peat land areas and investigation of peat failures

1.2 Project Description

The Services that form this project comprise carrying out a detailed scientific assessment, using available data and data provided, along with appropriate site visits, to determine the main conditioning and triggering factors that led to three peatland landslides that occurred in Counties Donegal (Meenbog), Leitrim (Shass Mountain) and Kerry (Mount Eagle) in 2020. The project will seek to characterise the environmental setting of the landslide sites, determine the main conditioning and triggering factors to the failures and further determine any shared conditions that may identify susceptibility in three additional areas of interest (control sites) to GSI and NPWS.

The three failures in question all occurred during 2020. The failure at Meenbog occurred on the 12 November during the construction of a wind farm. The failure at Shass Mountain occurred on the 28 June, immediately upslope of the ‘Dawn of Hope’ bridge, on the downslope edge of an area of forestry, but extending upslope into the forestry. The Mount Eagle failure occurred on the 15 November, within an area of forestry and including an open area of blanket bog upslope of the forestry.

The results of this assessment may be used to help inform the improvement of current guidance and policy documentation on peatland management (relating to peatland failures and peatland stability) produced by NPWS and GSI including the potential to update the National Landslide Susceptibility Map, to assist Local Authorities and other related bodies concerning peat failure contributory and trigger factors, including land use/human activity on peatlands in Ireland.

This Report covers Task 1 of the Specification of Requirements, namely: *“Conduct a comprehensive literature review focused on the conditioning and triggering factors to peat failures and peat stability. The review should also incorporates aspects of land use and the examination of potential conditioning and triggering factors related to the main land uses (including afforestation (drainage patterns/growth stage of plantation etc.), peat-cutting factors/drainage and cutting methods e.g. 'sausage -machine' cutting etc.), land use change and the physical and geotechnical characteristics of peat failures in Ireland and internationally (the latter where environmental conditions are comparable to those in Ireland).”*

1.3 Terminology

The following terms are used throughout the report and an explanation of their meaning is included here for clarity.

- **Peat**: sedentarily accumulated material consisting of at least 30% (dry mass) of dead organic material
- **Acrotelm**: The relatively thin upper layer of the peat, which in intact peatland is typically under aerobic conditions. Thickness can vary, from 0 to > c.40cm, depending on topography and hydrology. Near surface material is relatively undecomposed and more permeable than the underlying catotelm.
- **Catotelm**: Lower layer within a peat body, characterised by more humified plant remains in a permanently saturated anaerobic environment. Lower permeability that the acrotelm, and lower water storage capacity (permanently saturated when intact), although this depends on a number of factors.
- **Blanket Bog**: Peat deposited on upland areas with poor drainage where the number of rain days exceeds 200 days per year. Peat will accumulate wherever the drainage is impeded and where the slope is typically <20 degrees (Hobbs, 1986). Blanket bog is generally found on peat of over 0.5m thickness whereas heath is generally found on shallower peat. Blanket bogs are complexes which combine several congruent and hydrologically inter-related peatland sites into a continuous peatland system. Within the complex, the underlying peat varies considerably in depth and humification, according especially to the angle of the slope and the degree of waterlogging.
- **Raised Bog**: Peatland characterised by an elevated dome of peat, the surface of which is isolated from the surrounding groundwater table and receiving water solely from precipitation. Generally formed in depressions occupied by shallow lakes. Begins with the accumulation of fen peat, until the fen peat layers thickens so that the roots of plants on the surface are not in contact with the groundwater and have to rely on rainwater. This causes a change in plant type to those that survive in more acidic conditions (such as Sphagnum). The continued accumulation of material raises the surface of the bog above the surrounding landscape.
- **Undrained Shear Strength**: Undrained shear strength (c_u) refers to the strength of soil in situations where the excess pore water pressures developed during shearing cannot dissipate and at which failure takes place. The undrained strength of a soil applies in the short-term, for example during construction and until construction-induced pore water pressures dissipate.
- **Drained Strength:** The drained strength of a soil refers to the shear strength of a soil when the pore pressures generated by shearing dissipate rapidly or are not present at all. It is a measure of the long-term strength of a soil, recorded as an effective friction angle (ø’) and effective cohesion (c’).
- **Peat Pipes**: An underground channel, typically at the base of a peat deposit, that water flows through. Note however that peat pipes may also occur at other levels within a peat body. Not all mechanisms for their formation are understood.
- **Conditioning factors**: Conditioning factors are characteristics of the peat or the landscape that may predispose an area to being susceptible to a peat failure.
- **Triggering factors**: Triggering factors are specific events or occurrences that may be directly linked to the onset of a peat failure.
- **Landslide susceptibility**: A quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area. Susceptibility may also include a description of the velocity and intensity of the existing or potential landslide.
- **Hazard**: A condition with the potential for causing an undesirable consequence. The description of landslide hazard should include the location, volume (or area), classification and velocity of the potential landslides and any resultant detached material, and the probability of their occurrence within a given period of time.

- **Natural Drainage**: Comprises naturally occurring surface and subsurface drainage, in the form of overland flow, streams and rivers.
- **Artificial/Man-Made Drainage**: The alteration of a natural drainage pattern through the excavation of ditches, drains, ponds, etc., usually to reduce the water level.

2. Peat Failure Classification

2.1 Types of Failures

There are numerous general classifications available for landslides, but most are based on morphological factors and provide very little discrimination with respect to the various types of peat failures. Hutchinson (1988) is one of the few to specifically identify peat as a failure material. Both peat slides and bog slides are noted under the general description of translational failures, however no descriptions of what constitutes a peat slide or bog slide is provided. Dykes and Warburton (2007a) used the classification system from Hutchinson (1988) as the starting point for the peat failure definitions described below.

There are only a few formal classifications of peat failures that use essentially morphological factors; however, these do provide a starting point for peat failure classification based on contributory factors, see Table 2-1 below. The failure types are also shown schematically in Figure 2.1. These are taken from Dykes & Warburton (2007a). It should however be noted that not all failures would necessarily fall within one of the peat failure types listed below, and some may be a hybrid type that exhibits characteristics of a number of different types of peat failures, especially in relation to the formation of bog slides, bog flows and peat flows.

Table 2-1: Example of peat failure classification (Dykes and Warburton (2007a)

Type	Description
Bog bursts	Flow failure of raised bogs
Bog flow	Flow failure of blanket bogs
Bog slides	Shear failure and sliding of blanket bogs on a shearing surface
Peat slides	Shear failure at peat–mineral interface in blanket bogs
Peaty-debris slides	Shear failure within mineral substrate beneath blanket bogs
Peat flows	Failures of other types of peat deposits including flow failure caused by head-loading

The classification of peat failures into categories such as those given in Table 2-1 allows assessment of the following through reference to historical peat slides of similar type:

- Improved prediction of most likely failure locations
- Likely volume of failures
- Likely run-out distance of failures
- Potential environmental impacts of failures

For example, the main triggering factor for numerous peat failures is considered to be intense rainfall (Boylan et al, 2008). In many cases, these failures occur in shallow peat on steeper slopes with relatively high shear strength and the volume and run-out distance tends to be limited; examples of these are failures that occurred at Pollatomish (in 2003), and failures on the Inishowen Peninsula (in 2017), in contrast to larger-scale peat failures that have occurred in deeper peat on shallower slopes, for example at Derrybrien (in 2003) and at Meenbog (in 2020).

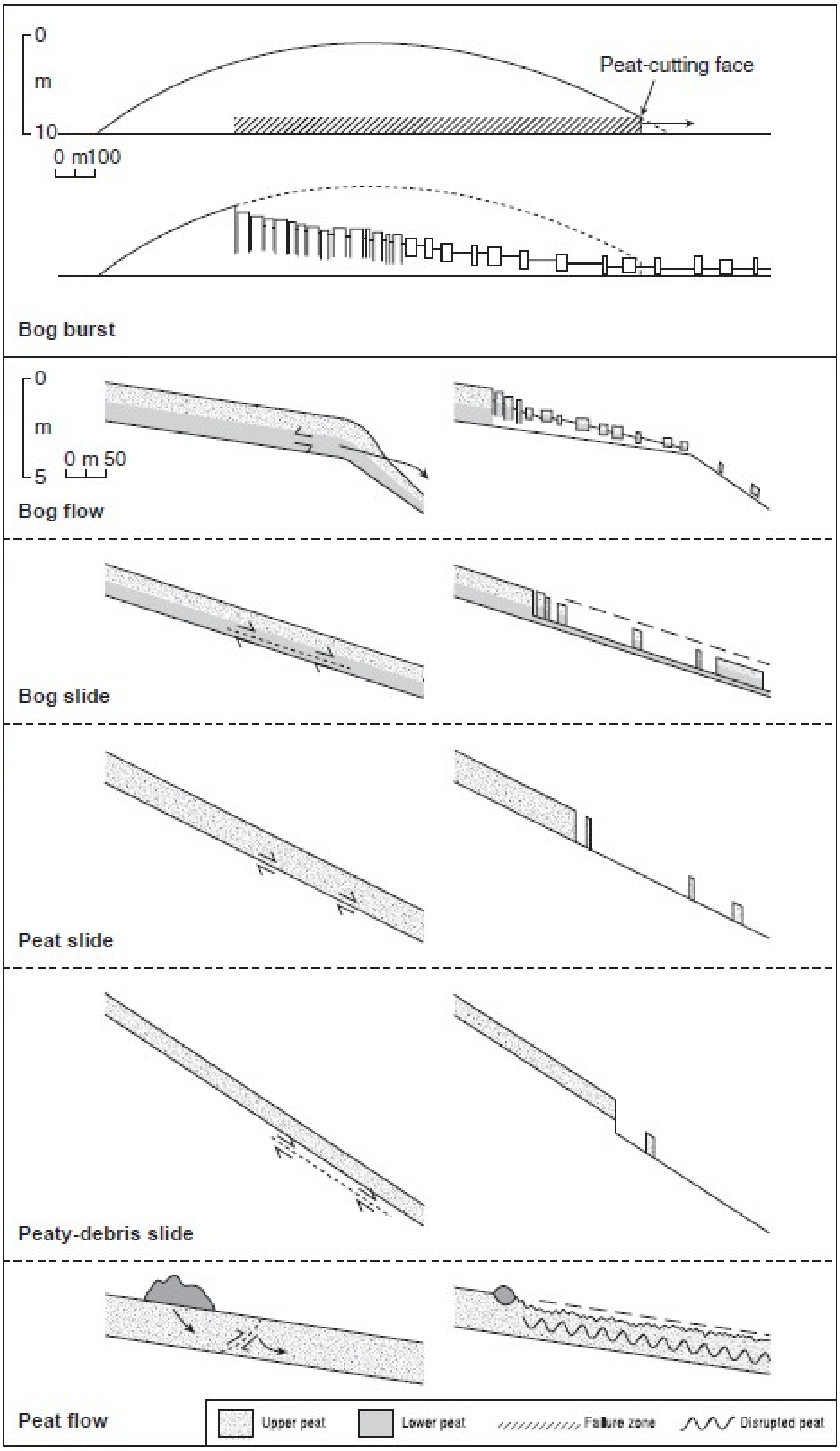

Figure 2.1: Peat Failure Types (Dykes and Warburton, 2007a)

2.1.1 Bog Bursts

Bog bursts involve large quantities of peat (usually greater than 10,000m^3; Mills, 2002) in spreading failures where the landslide retrogresses (cuts) upslope in 'slices' from the point of failure and an outflow of slurried peat carries intact blocks downslope, usually entering existing surface water channels. Large-scale bog bursts are often associated with raised bogs where there is an upper fibrous layer (acrotelm) over a lower body of weak amorphous peat (catotelm). It appears that the peat is in a near-fluid state prior to failure, possibly as a result of build-up of excess pore water pressure within the peat mass (Colhoun et al., 1965; Alexander et al., 1986) or deep cutting of deep face banks near wetter parts of a bog.

2.1.2 Bog Flows

Bog flows are similar to bog bursts but are associated more with blanket bog areas and are typically more limited in extent. Source areas tend to be long and narrow, and the failures are characterised by the presence of large rafts of intact peat being transported downslope.

2.1.3 Bog Slides

A failure of a blanket bog dominated by the sliding of intact peat over a failure surface within, or at the upper or lower surface of, the catotelm (Warburton, 2015). Larger examples of bog slides appear to involve the failure of peat at a specific location such as a sharp convex break in slope, with retrogressive failure upslope. This is often characterised by the upper, more fibrous section of peat sliding over a more amorphous peat at depth. Low gradients (5-8 degrees) and moderately deep peat (1-3m) appear to characterise these failures (Dykes and Warburton, 2007a).

2.1.4 Peat Slides

A failure of blanket peat-covered slopes characterised by the sliding of the peat mass over a failure surface at the interface between the peat and the underlying mineral substrate, or within the substrate below the base of the peat (Dykes & Warburton, 2007a).

Both peat slides and bog slides occur when the shear strength of a particular layer of material within a peat-covered slope, or the shear strength of the contact plane between two layers, is exceeded by the disturbing forces acting on the slope in the same way as for any other shallow translational landslide.

2.1.5 Peaty-Debris Slide

A failure best described as a "shallow translational failure of a hillslope with a mantle of blanket peat in which failure occurs by shearing wholly within the mineral substrate and at a depth below the interface with the base of the peat such that the peat is only a secondary influence on the failure" (Dykes & Warburton, 2007a).

2.1.6 Peat Flows

A flow failure in any type of peat caused by head loading (a bearing capacity failure caused by loading from an external source, typically man-made), or a failure of any type of peat not covered by the preceding terms (Warburton, 2015).

3. Literature Review

3.1 Introduction

FT undertook a review of available literature on peat slides, focusing on Irish examples but also including failures from locations such as England, Scotland and Canada. A comprehensive list of the papers and references reviewed is provided in the References and Bibliography. The reviewed publications were gathered from a number of sources, including FT's own library of books/papers, publications such as the Quarterly Journal of Engineering Geology and Hydrogeology, Landslides and Géotechnique, as well as previous GSI publications. Internet searches for keywords such as "peat failure", "peat instability" and others were used where necessary. Cross referencing from already held papers provided a significant number of previously unknown papers.

3.2 Relevant Papers

The papers reviewed cover peat failures between 1896 and 2020, with over 50 no. individual failures identified, typically located on blanket bog. The majority of papers reviewed are dated from before 2014, and only a limited number appear to have been published on this subject between 2014 and 2023 (<10 papers). The failures range in size from small (<1,000m^3) to extremely large (around 5M m^3). This, however, only represents a small proportion of all the failures recorded by the GSI within the national landslide database, which currently lists in excess of 2,500 landslides. Within the GSI database around 50-55% of the recorded failures are related to peat even though peatlands cover c.20% of Ireland.

A review of these papers enabled the provision of a summary of the recorded conditioning and triggering factors for Irish peat failures. In addition, papers relating to failures in the UK and further afield have also been reviewed to determine if different conditioning/triggers factors are present in other locations. It is not intended to provide a detailed description of each paper and peat failure within this report; however, the following provides an overview of the findings.

Peat Failure Classification
Dykes, A.P. & Warburton, J. (2007a) contains a proposed classification scheme for the different types of peat failure, namely Bog Burst, Bog Flows, Bog Slides, Peat Slides, Peat Flows and Peaty-debris slides. This classification has been summarised in Section 2.1 Types of Failures and Figure 2.1 and is used throughout this report. Dykes (2022) points out that the precise mechanism of failures in the case of bog bursts and bog flows is however still unknown.

Landsides and Peat Failures in Ireland
Dykes (2022) reports that landslides involving peat are relatively common in Ireland; upland areas of Great Britain; and sub-Antarctic islands. However, he states that bogflows and bog slides are less common types of peat failure and almost unknown outside of Ireland. The stated aim of Dykes (2022) is to determine the extent to which new bog slides and bogflows are consistent with previous examples in terms of their contexts, characteristics and possible causes, particularly relating to commercial forestry operations.

Historical Reports of Failures

The earliest peat failure reviewed within this literature review occurred on 29th December 1896, at Knocknageeha, Co. Kerry. A description of this failure is recorded in the records of the Dublin Naturalists Field Club, from 1897. This describes the bog in the area bursting, and a 'fluid mass' pouring down the valley of the Owenacree river. While not contained within the report on the failure, it has since been estimated that this is the largest recorded peat failure in Ireland, with an approximate 5M m^3 volume of displaced material. No specific conditioning or triggering factors are identified, but reference is made to a preceding dry summer and wet autumn, with a 'heavy downpour' recorded on the day before the failure occurred. There is also reference to a deep peat cutting, and a failure to adequately drain the area.

While earlier peat failures have been recorded on the island of Ireland (Feehan & O'Donovan, 1996), these are mostly subjective reports, with little information provided in the way of conditioning and triggering factors. As an example, Ousley (1788) describes in general terms a large-scale bog failure that occurred close to Dunmore, County Galway in March 1745, apparently immediately after an intense rainfall event.

Griffith (1821) records the findings of a visit to a failure in Kilmaleady, Co Offaly, which described turf cutting of up to 10m depth and the presence of a blue clay at the base of the peat. The report describes that "the lower pulpy and muddy part of the bog" gave way, leading to a failure that covered around 150 acres. Therefore, peat cutting deep into the weaker catotelm peat is implicated in these two historic failures.

Recent Reports of Peat Failures

One of the most recent papers reviewed is by A.P. Dykes (2022), and remotely (due to pandemic restrictions) assesses three peat failures: Meenbog, Shass Mountain and Mount Eagle, which are the topic of this GSI/NPWS commissioned study. Dykes links these failures to elevated rainfall in two cases (Shass and Mount Eagle) and construction activities in one (Meenbog) and discusses the potential impact of the presence of commercial forestry at each of the failure sites. Only a limited number of papers (<10) appear to have been published relating to this topic between 2014 and 2023.

Failure Frequency

Several papers have reviewed the frequency of failures, with general indications that failures are becoming more frequent (Evans (2007), Boylan, Long & Jennings (2008), Dykes (2022), Long (2022)). This (according to Dykes) is likely due to a variety of reasons, not least of which is the development of wind farms on upland peat sites over the last 20-30 years, as well as a general trend of increasing average rainfall (associated with human induced climate change) as well as more frequent intense rainfall events (Dykes, 2022). However, this apparent trend may also simply be due to more awareness of peat failures, meaning that more failures may be reported but the overall frequency has remained the same (Dykes, 2022, Long, 2022).

Conditioning and Triggering Factors

Conditioning and triggering factors for peat failures are discussed in several papers by: Dykes, A.P. & Kirk, K.J. (2001 and 2006), Dykes, A.P. & Warburton, J. (2007b), Boylan, N., Jennings, P. and Long, M. (2008), Long, M, Jennings, P and Carroll, R. (2011) and Dykes, A.P. (2008b). Dykes, A.P. & Kirk, K.J. (2001) summarises published examples of peat failures where potential conditioning factors have been identified. These factors are described further in Dykes, A.P. & Kirk, K.J. (2006), where a series of factors which 'may contribute' to movement in peat are identified, including:

- climatic factors (rainfall, extreme weather events, climate change)
- topographic factors (slope morphology, erosion, presence of relict structures)
- peat strength, presence of peat pipes
- land use (peat excavation, erosion, external loading)

Common conditioning factors are also described in Dykes (2008b), which notes that, based on a limited sample pool, bog flows are more likely to be associated with:

- concave breaks in slope, as well as
- following prolonged wet periods,

and that bog slides are linked to:

- convex breaks in slope,

with heavy rainfall the triggering factor most commonly reported for all failure types.

A summary of conditioning and triggering factors from the reviewed literature is provided in Table 4.1 and in more detail in Appendix A.

3.2.1 Peat Depth and Slope Angle

The link between peat depth and slope angle is discussed in Boylan, Long & Jennings (2008) and Dykes (2022), stating that an increase in slope angle generally corresponds to a reduction of the depth of peat. Dykes (2022) also divides the locations of known failures into bog flows, bog slides and peat flows, indicating that bog flows and peat flows are typically recorded in areas with a slope of <5 degrees, but with a slope of 5 to 7 degrees these failures become bog slides, showing a change in failure mechanism as slope angle increases. This zone of slope angle also contains the majority of recorded peat failures. This likely represents a slope angle range that is shallow enough for a significant depth of peat to accumulate, but steep enough that a failure can occur once the peat exceeds a certain thickness, provided certain conditioning factors are present (Dykes and Selkirk-Bell, 2010), or once the peat is subject to an external trigger.

3.2.2 Physical Properties of Peat

The effect of the physical properties of the peat on stability is discussed in Long (2005), Dykes (2008a), and Boylan and Long (2014). These papers show that the physical properties of peat are significantly affected by:

- the stress history of the peat,
- the level of decomposition within the peat mass, as logged to the Von Post classification, and
- the moisture content of the peat.

Each of these physical properties can also be affected by the land use history of a specific location.

3.2.3 Hydrology

A series of hydrological controls on peat failures are described in Warburton et al (2004) and Evans (2007), which include the effect of groundwater flow on the peat/soil interface. Several notable characteristics were noted in this paper;

- failures associated with summer thunderstorms, and
- the concentration of failures along pre-existing drainage features.

The failures reviewed in those particular papers are shallow peat slides in the Pennines.

The presence of pipes at the base of peat has also been noted as a common feature in several peat failures (Carling 1986, Long & Jennings 2006 (and references therein), Dykes & Warburton 2007b).

A study of peat failures on subantarctic islands and comparison with similar failures in Ireland is presented in Dykes & Selkirk-Bell (2010). This paper examines numerous shallow failures on peat covered hillsides, which appear to occur at a much greater frequency than peat failures in Ireland. These failures are typically described as peat slides which fail along a planar shear surface at the base of peat, such as an iron pan, which seems to limit the thickness of peat that can be deposited on a slope before a failure occurs. Some similarities are present when compared to some Irish peat failures, specifically in respect of failures on slacker slopes, however the frequency of failures is significantly higher on subantarctic islands compared to Ireland.

3.2.4 Vegetation and ecosystem condition

The vegetation present around failure areas is discussed in several papers, such as Dykes & Kirk (2006) as being of significance in peat failures. Therefore, changes in peatland vegetation including removal of vegetation (bare peat) or colonisation by non-bog vegetation may have implications for peat stability via a number of mechanisms that impact on normal ecosystem functioning. There are complex interactions between plants and water and peat in bogs (Cowenberg et al., 2022). Bogs in their natural state are self-regulating ecosystems and modifications to any one of the three key elements of plants, soil or water levels can result in changes to the other two such that ecosystem functioning is impaired and this in turn may have implications of peat stability.

Many scientific papers report that species composition and vegetation structure are key indicators of bog ecosystem condition and functioning and these and other ecosystem factors are commonly used in habitat condition assessment of bogs (e.g. see Irish Wildlife Manual No. 79, Perrin et al., 2014). However, there are very few examples reported in which the type of vegetation on a peat bog has been directly linked to a peat failure.

The vegetation present around failure areas is discussed in several papers, such as Dykes and Kirk (2001), which notes that the presence of *Sphagnum* species (which require wet ground conditions to thrive) on a hillside may also indicate the presence of peat pipes, which can have a negative impact of peat stability.

Blanket bog is a naturally treeless habitat and the change to forested vegetation leads to changes in the properties of the peat (moisture content and decomposition etc, see section 3.2.2) which can in turn impact on peat stability. The presence of forestry vegetation has been cited as a contributory factor for the Derrybrien failure (Lindsay & Bragg, 2005), in relation to the presence of drainage and ploughing furrows being lines of weakness that failed; and in preventing the establishment of a competent root mat; and that evapotranspiration from trees is also much greater than from peatland vegetation (Sarkkola et al., 2010), which greatly reduces the water table depth, exposing deeper layers of peat to drier and more oxic conditions (Pyatt et al., 1992; Sloan et al., 2018). Loading from the growing weight of timber in plantation forestry is also considered a factor that can impact peat stability (Lindsay & Bragg, 2005).

The potential importance of the botanical composition of peat soil as a controlling factor for the properties and geotechnical behaviour of the peat was examined by Foteu Madio, E.S. & Dykes, A.P. (2018), with particular reference to three failure sites (at Straduff Townland; Slieve Anierin; and Slieve Rushen) in upland areas of the north midlands of Ireland. However, only limited conclusions were drawn from this study due to the similarity of the peat within the three sites investigated. This study concludes that the upland blanket bogs of northwestern Ireland appear to be formed from essentially the same assemblages of plant species, dominated by sedges (mostly represented by *Eriophorum vaginatum*), and therefore having similar physical and botanical characteristics. The study did indicate that the monocotyledon peats at these sites generally have higher tensile strengths than *Sphagnum* bog peat locations.

3.2.5 Afforestation

The influence of forestry on peat in general terms is covered by Anderson et al (2000), Anderson (2001), and Sloan et al (2019) describing the effects of afforestation on:

- peat thickness,
- moisture content of the peat, and on
- the integrity of the peat mass.

These papers indicate that once closure of the forest canopy occurs:

- peat shrinkage and ground subsidence due to a fall in the water table can be expected.

These papers include discussion on the change in water levels and peat thickness recorded at a site in Scotland over a 50-year period. Anderson (2001) also refers to the issue of peat cracking within forestry, in terms of rewetting and restoring peat bogs. This paper states that:

- cracking can be expected in any plantation on a blanket bog, and that:
- this cracking will occur provided that non-fibrous peat exists within the zone where sufficient drying occurs, classed as the upper 1m of the peat profile.

4. Conditioning and Triggering Factors in Peat Failures

A summary of the main (conditioning and triggering) factors in peat failures cited in the literature reviewed is provided in the table below. Specific conditioning and triggering factors are discussed in more detail in the following sections.

Conditioning factors are characteristics of the peat or the landscape that may predispose an area to being susceptible to a peat failure.

Triggering factors are specific events or occurrences that can be directly linked to the onset of a peat failure. They have a rapid or immediate effect on peat stability whereas conditioning factors may influence peat stability over a longer period of time (years to hundreds of years).

A detailed breakdown of cited conditioning and triggering factors of known peat failures as noted from the literature reviewed is included in Appendix A.

It should be noted that at any failure site it is a combination of factors that are significant, and that any single factor is unlikely to be sufficient to lead to a peat failure (based on the papers reviewed for this report).

An example of a single factor could be forestry plantation drainage furrows which in combination with a number of other factors such as, for example, if located on deep peat, or on a convex slope, would be considered a key factor in reducing stability causing collapse of a peat mass. In other instances, forestry drains may have controlled the extent of an adjacent peat failure (either limiting or extending a failure).

Table 4-1: Examples of potential conditioning and trigger factors for peat failures

Conditioning (C) or Triggering (T) factor	Description
Peat condition (C)	Type, depth, strength, structure, decomposition, water content. The properties of a bog peat soil are intimately bound up with the characteristics of the bog habitat that form it. Engineering properties of peat can be affected by historical and current land use.
Hydrology/Hydrogeology (C)	Stream density, drainage lines and flushes, quaking peat, bog pools. These are natural features in peatlands. Peat pipes (subsurface flows) may also occur and can be natural or may form by human impact. Seepage from the base of peat at exposures can also occur and mostly result from human activity in creation of peat exposures but can also occasionally be from animal activity. Bog hydrology can be altered by many land uses and activities.
Ecology/Vegetation (C)	Vegetation roots and partially decomposed plant matter in bogs form a top layer or mesh of fibrous matter (acrotelm) above more humified or decomposed weaker peat (catotelm). Vegetation can be modified or completely altered by reclamation/ forestry/ drainage/ grazing stock management/ peat extraction etc. which can in turn alter the above properties of the peat soils including strength and stability.

Conditioning (C) or Triggering (T) factor	Description
Subsoil (C)	Type, strength, structure, permeability
Bedrock (C)	Rock type, strength, structure, weathering, permeability
Land Use – Plantation Forestry (C)	The presence of forestry is in most instances associated with the presence of drains /or furrow and linear spoil mounds within the plantations. These alter the natural hydrology of the peatland and change peat properties and the cohesive integrity of peatlands through desiccation; shrinkage; cracking; pipe formation and other effects
Land Use – Infrastructure (C/T)	The construction of infrastructure (public and forestry roads, windfarms, etc.) can lead to both loading (filling) and unloading (excavation) of peat which can cause immediate failure. The infrastructure itself can also lead to long-term changes in peatland hydrology and vegetation including alterations in surface flow pattern and internal drainage patterns leaving peatlands more vulnerable to failures.
Land Use – Fires (C)	Fires have multiple effects including hydrological changes from removal of vegetation cover, reducing and increase in surface run-off through reduction of the amount of water taken up by plants, leading to saturation alternating with desiccation of the peat surface which can cause erosion, shrinkage, cracking etc. This can allow water ingress to lower peat layers or sub-peat substrate.
Land Use – Drainage (C)	The presence of drains results in hydrological, vegetation and acrotelm changes including lowering of the water level in a peatland and, importantly, alteration of surface flow patterns that in intact bog maintain diffuse bog surface flows. When drains are blocked (or too shallow) they trap water in the peat, saturating the peat, potentially reducing the shear strength, and increasing the risk of failure. However, blocking of drains can also be beneficial to improve ecosystem functioning and the resilience of the peat and the blanket bog ecosystem to weather extremes.
Land Use - Peat Cutting/Extraction (C)	Peat cutting can lead to the creation of unstable peat banks or the impounding of water within peat cuttings. Removing vegetation can leave open areas where water can collect, saturating the peat. Mechanical cutting of peat alters vegetation, acrotelm, hydrology, weakens the peat structure, and provides a preferential path for water ingress, which can lead to failure. The orientation of mechanical cuts can alter the impact, with cuts across a slope trapping water but cuts down a slope draining water from a peat body.
Land Use - Peat Loading/Construction on Peatlands (T)	Stockpiling of peat or other materials on a peat bog following excavation/extraction causing bearing capacity failure within the peat (peat flow), such as at Derrybrien (2003).
Land Use - Agriculture	Drainage/reclamation/high stock density/grazing management/trampling etc. alter bog vegetation, peat, and bog hydrology with multiple consequences such as denudation/desiccation/decomposition/ shrinkage/cracking/erosion.
Topography/Geomorphology (C)	Concave/Convex breaks in slope. Peat failures may occur on both shallow and steep slopes.
Dry Weather (C)	Excessive drying of upper layer of peat leading to cracking of peat can provide a preferential pathway for water ingress when rain falls, which can lead to peat failure through saturation of the lower peat weaker layers.
Substrate conditions at base of peat (C)	Presence of an impermeable layer or soft clay at the base of the peat can provide a slip surface for the peat (a peat slide rather than shear failure of the peat).
Peat Pipes/Soil Pipes (C)	The presence of peat pipes, while allowing drainage of the peat, can cause erosion at the base of the peat and following rainfall events result in the buildup of a water pressure head.

Conditioning (C) or Triggering (T) factor	Description
Rainfall (T)	Sudden intense rainfall leading to excess porewater pressures in peat, leading to failure. It can also cause erosion/scouring of shallow peat on steep slopes. Increased frequency of extreme rainfall events is linked to human induced climate change which may impact peat stability.
Anthropogenic Climate Change (C)	Apparent increase in annual rainfall over the past 50 years, characterised by more frequent intense rainfall events, especially in summer. Higher average temperature in summer may lead to more drying of upper peat layers during summer, increasing near surface cracking and providing additional pathways for water to flow into the base of the peat. It can also change species composition allowing heath species to invade which can further alter natural ecosystem structure and functioning. No detailed research appears to be available on the impact of climate change on peat stability.

These factors can be broken down into conditioning and triggering factors, and some of the main factors are discussed below.

4.1 Peat Condition, Strength and Morphology

The shear strength of peat is considered to be one of the main controlling factors in the development of peat failures. Boylan, et al (2008), Boylan and Long (2014), and Long (2005) all discuss both the effect of peat strength and the difficulties in accurately measuring the undrained (short term) strength, especially in the field. The shear strength of the peat is linked to the degree of humification, the stress history of the peat, the current effective stress within the peat, and the moisture content, with increases in humification and moisture content typically leading to a reduction in the shear strength (Boylan et al, 2008, Long & Boylan, 2014). The use of geophysics (shear wave velocity) to determine undrained shear strength is discussed in Trafford and Long (2020) which indicates, based on the location studied, that a strong relationship between the two values can be determined when moisture content is taken into account.

Drained strength can only be measured from laboratory tests; however, studies have shown significant variability in these values, partly related to the degree of humification of the peat (Long, 2005).

In addition to undrained and drained strength, Dykes (2008c) discusses the impact of the tensile strength of peat on the occurrence of peat failures and believes that the tensile strength is an important factor in the occurrence of peat failures, specifically bog flows, where the tensile strength of the acrotelm is an important controlling factor on the development of a failure on a near liquid catotelm layer.

The land use history can also be an important factor in the strength of a peat deposit. An example of this is an afforested area, where the presence of trees over a long period of time can lead to a change in the hydrological conditions, resulting in drying and cracking of the peat, not only reducing the strength of the peat mass but also allowing ingress of rainwater run-off to access the deeper weaker catotlem peat and/or the peat/peat subsurface interface.

The subsurface morphology of the peat layer (the shape of the surface of the base of peat) can also be a factor that influences failure, specifically through the presence of small-scale features, such as valleys/deeper pockets of more decomposed peat. The initiation of failures in depressions and watercourses of rivers has been noted for a number of failures. During the early stages of peat development, peat formed first in waterlogged depressions and in channels where water flowed. This peat formed under high nutrient conditions from rainfall and the surrounding mineral soils, causing an increased level of decomposition in these depressions. The degradation of peat strength with increased decomposition may make these locations more prone to failure. The susceptibility of these channels to failure may be exacerbated by the concentration of runoff waters within the peat mass at these locations (Boylan et al, 2008).

4.2 Rainfall

High-intensity rainfall or periods of prolonged rainfall are the most commonly cited triggering factors for peat failures however correlation is not necessarily causation and additional and more site specific factors must also be involved as otherwise peat failures would occur on all peatland sites in a locality experiencing the same high rainfall event. The numerous failures that occurred at Pollatomish, Co. Mayo and in the Shetland Islands on the same night in September 2003 occurred during a period of intense, localised rainfall (Boylan, Jennings & Long 2008, Dykes & Warburton 2008). However, shrinkage and cracking of the peat surface as a result of the dry summer beforehand may also have predisposed these locations to failure by providing pathways for the rainfall to the base of the peat. Similarly, a series of at least eight peat failures occurred in a relatively small area near Geevagh, Co. Sligo (Figure 4.1), during August 2008 following heavy rainfall (Dykes and Jennings, 2011).

More frequent high intensity rainfall events, which are predicted to increase as a result of anthropogenic climate change, may be linked to an increase in the frequency of multiple failures within a specific area (failure clusters) (Evans, 2007) though pre-disposing factors are also likely to be involved, such as for many of the numerous landslides (40 plus) that occurred at Pollatomish.

A likely failure mechanism is that following heavy rainfall, infiltration of surface water into the ground results in a build-up of pore pressures and reduced effective shear strength, particularly at the interface between the peat and the mineral soil. This can lead to a retrogressive type of failure. Secondary effects include possible swelling of the peat bog, increase in loading due to ponding, together with possible softening.

There is also a possible link between the impact of intensive rainfall events and the presence of peat pipes at the base of the peat, leading to high water pressures should the rainfall amount exceed the output capacity of the pipes (Dykes and Warburton, 2007b), or also if the pipes are blocked in some way, such as by vegetation.

A sequence of dry periods followed by periods of heavy rainfall has also been recorded prior to peat failures. In these cases, drying out of the upper peat (often caused by human activities), particularly in areas of thinner peat, is considered to have resulted in the development of near-surface cracks which could facilitate rapid ingress of water into the base of the peat following an intensive rainfall event. This would be reflected in the frequency of failures in late summer/autumn, as referred to in Dykes (2022). A study of UK peat failures (Mills, 2023) indicated that peat slides were more likely in summer/autumn, but that the occurrence of bog bursts was more evenly spread throughout the year.

Figure 4.1: Example of failure (peat slide) in blanket bog at Corry Mountain, Co. Sligo
(photo courtesy of Dr Paul Jennings, from Dykes and Jennings, 2011)

4.3 Topography/Geomorphology

In terms of elevation, in Ireland peat failures have typically been recorded between 300-500mOD (Creighton, 2006).

Slope morphology has been shown to provide possible initiation points for failures. A convex break in slope has been cited as a feature in a number of failures (Dykes, 2008b, Boylan et al, 2008). It is thought that the peat upslope of the convex slope is notably thicker and weaker than the well-drained peat below the break. In the event of rupture at the break this leads to a retrogressive failure of peat upslope with little passive resistance provided by the lower slopes.

Concave breaks in slope have also been associated with bog slides (Boylan et al, 2008). In this case a relatively well drained body of peat can fail due to a build-up of lateral pressure on the upslope face. Alternatively, a failure mechanism, analogous to a piping failure underneath dams, has been noted where springs are present in locations immediately down-slope of the relatively well drained peat body. High pore pressure gradients within the peat can lead to undermining of the relatively well-drained peat body resulting in a breach and loss of lateral support to peat upslope.

Figure 4.2 shows a plot of some historical data of pre-failure slope angles at a series of failure sites across Ireland. The failures are grouped in terms of peat/bog slides and bog bursts. From Figure 4.2, it can be seen that failures occur at a wide range of slope angles. The wide range suggests that several other contributory factors are present at failure sites. In general, recorded failures occur at slope angles between about 4 and 8 degrees, though in rarer circumstances such as where peat has been affected by human interference, such as through cutting of peat, failures have occurred on slopes as shallow as 2 degrees. The failures on slopes of between 4 and 8 degrees may correspond to the slope angles that allow a significant amount of peat to develop that over time becomes potentially unstable when affected by a specific trigger (Boylan et al, 2008).

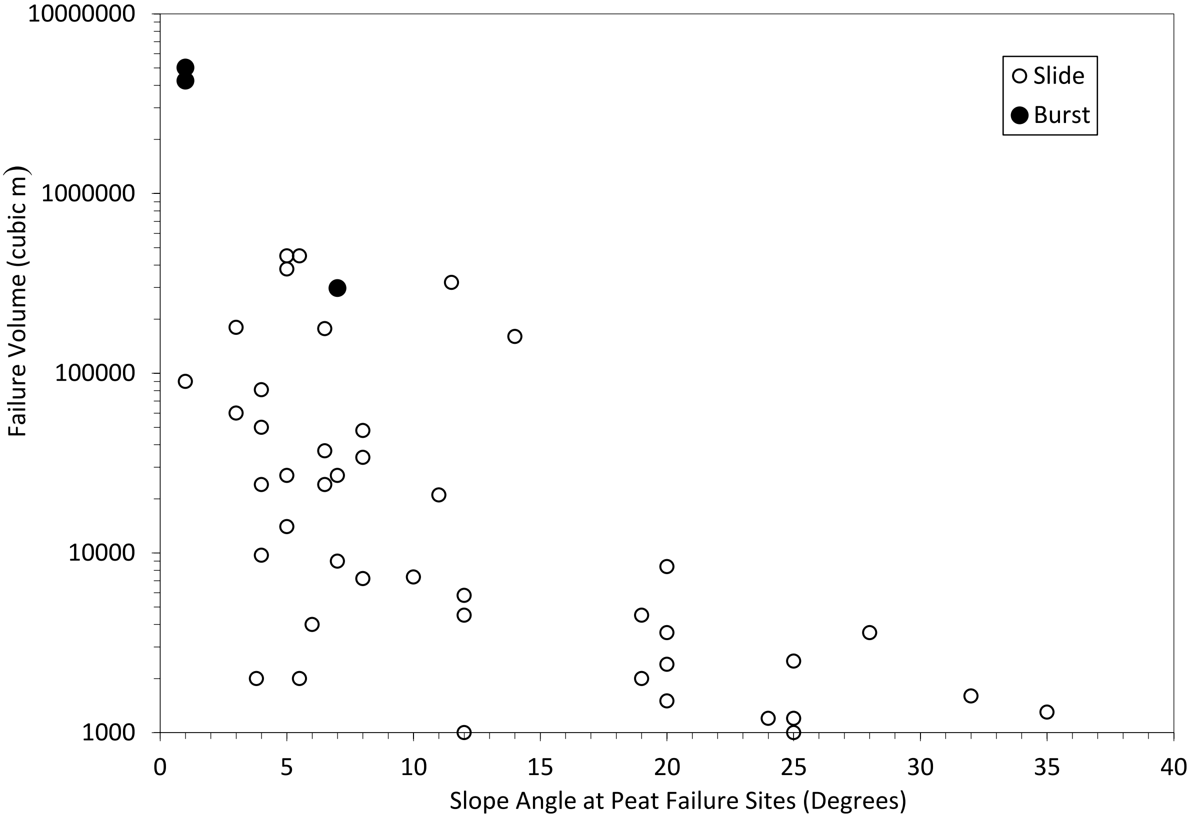

Figure 4.2: Slope Angles and Failure Volumes at Sites of Some Irish Peat Failures (update based on Boylan et al, 2008)

Notes:

(1) Peat failure data based on review of some 35 Irish failures from 19th, 20th and 21st Century.
(2) Peat failure data is based on reported information or field measurement.

The mobility of peat failures is well-documented with recoded instances of peat debris travelling many kilometres from the failure source. For example, peat debris from the 1896 failure at Knocknageeha was recorded in excess of 15km from the failure source. Following initial failure, peat debris tends to rapidly breakdown into slurry, which behaves as a viscous fluid. In many cases peat debris becomes confined and flows within a drainage line. Once peat debris has entered a drainage line it mixes with any water that may be present and becomes diluted which further increases its mobility and impact on the environment.

Run-out distance versus failure volume for a total of 44 reported peat failures is shown in Figure 4.3 (from Boylan, Jennings & Long, 2008). Run-out distance is defined as the horizontal distance from the downslope edge of the failure scar to the downslope limit of failure debris. As peat debris is notably mobile and can be relatively easily transported in water it is difficult, in many peat failures, to determine exactly where the downslope limit of peat debris is.

There is a general trend showing that run-out distance increases with failure volume, though there is a large scatter of results at larger failure volumes. The scatter may be attributable to many factors, such as degree of topographic confinement, presence of entrapped water in failure mass and the wash-out of debris along river courses (Boylan, Jennings & Long, 2008).

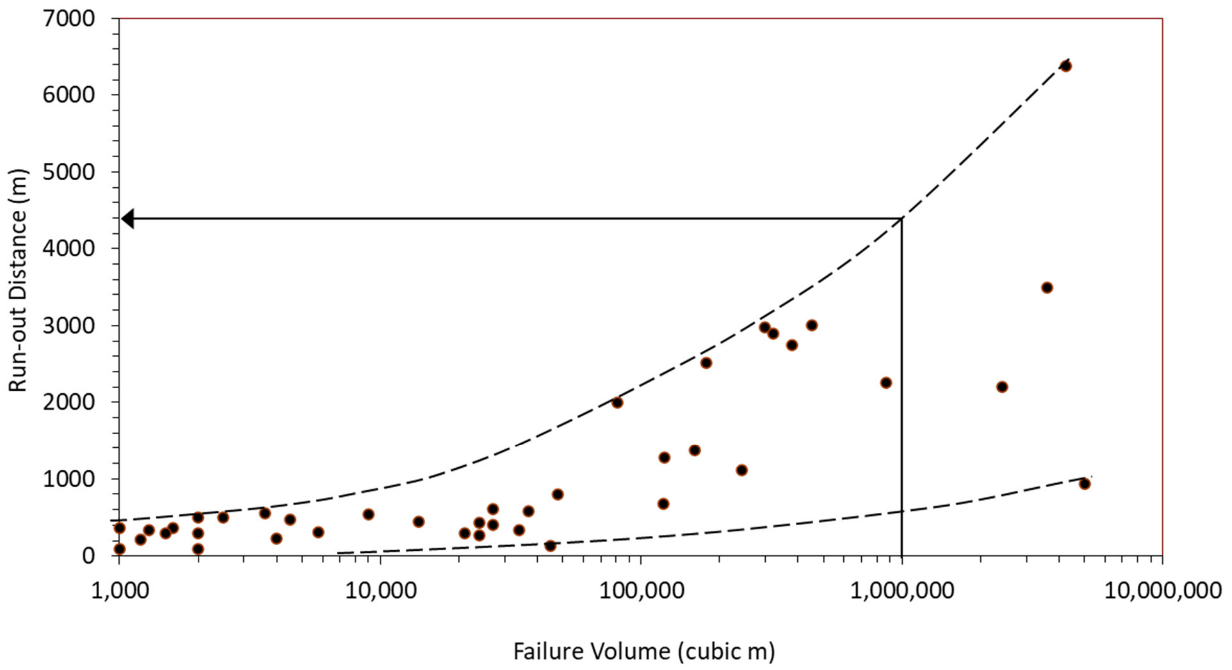

Figure 4.3: Failure volume versus run-out distance (reproduced from Boylan et al, 2008)

4.4 Hydrology/Hydrogeology

The permeability of the acrotelm layer within a peat deposit is described in Hobbs (1986) as being high near the surface (up to 10^{-1} m/s) reducing significantly at the base of the acrotelm (around 10^{-5} m/s). The permeability of catotelm peat is typically moderate to low, in the range of 10^{-5} to 10^{-10} m /s and decreasing significantly with humification, with blanket bogs using a network of macropores and pipes to transport water within the peat mass (Boylan et al 2008). The permeability of the catotelm layer of peat is dependent on several factors (Hobbs, 1986), including the botanical composition of the catotelm, the degree of humification (more humified = less permeable), the bulk density, the fibre content, the void ratio and the surface loading. The vertical permeability of peat is noted to decrease rapidly with increasing effective stress (loading). It should also be noted that there typically is a notable difference between the horizontal and vertical permeability of a peat deposits, with the horizontal permeability typically significantly higher, especially following loading of the peat.

However, it is worth noting that the acrotelm–catotelm division is not well-developed in all peats and can be disrupted, or entirely lost, in areas where drainage, over-grazing and peat cutting have been practiced (Warburton et al, 2004).

Hydrological and hydrogeological controls on peat failure mechanisms are discussed in detail in Warburton (2004), Evans and Warburton (2007), in relation to a series of failures on Dooncarton Mountain in Dykes and Warburton (2007b), and for a range of peat failures in Boylan et al (2008). In the cases reviewed by Warburton (2004) and Evans and Warburton (2007), failure mechanisms in peat can be affected by:

- an increase in the hydrological loading, such as from rainfall or snowmelt,
- an increase in hydrostatic/porewater pressure (rise in water level) within the peat,
- the generation of artesian pressures (upward pressure from below the peat) and
- swelling of basal peat.

The presence of pipes at the base of peat has also been noted as a common feature in several peat failures (Carling 1986, Warburton et al 2004, Long & Jennings 2006, Dykes & Warburton 2007b). The peat mass uses a network of macropores and natural pipes to transport water within the peat (Holden 2006). In the event of an extreme rainfall event, excessive water pressure within these pipes may lead to erosion of the soft peat material leading to the creation of failure planes.

Mills (2002) examined records of slope drainage for bog burst and peat slides reported in the literature and found a large proportion of the peat slide failure sites had drainage (both natural and artificial) direct into the heads of the failure, with piping recorded in 27% of the peat slides investigated. Forestry drainage has also been directly linked to a failure at Bellacorrick Forest (Hendrick, 1990). In the case of Bellacorrick, plough furrows within the forestry plantation were not connected to collector drains, which likely lead to ponding of water close to, and upslope of, a break in slope. Following prolonged heavy rainfall, this area would have become saturated and eventually failed.

4.5 Vegetation

The semi-natural vegetation present on a peatland rarely appear to be noted as a major conditioning factor in peat failures, however the type of vegetation present can provide information on the condition of the peat, and possibly a link to its susceptibility to failure.

Land use changes, particularly the conversion of undisturbed peatlands to plantation forests, can result in the loss of natural vegetation and peat subsidence, affecting peat stability and ecosystem structure. Replacement of peatland vegetation with tree vegetation as in afforestation of the peatlands is reported to have implications for peat stability (see 4.6.1).

The vegetation present around failure areas is discussed in several papers, such as Dykes and Kirk (2001), which notes that the presence of *Sphagnum* species (which require wet ground conditions to thrive) on a hillside slope may possibly indicate the presence of peat pipes, which can have a negative impact on peat stability.

Tomlinson (1981) describes the vegetation present around the head of a failure at Carrowmaculla, Co. Fermanagh, which indicated that vegetation associated with wetter areas of peat (such as *Sphagnum*) was present at the head of the failure.

Drainage of a peatland which leads to drying of the acrotelm can be observed by a change in vegetation to plant species that can tolerate drier conditions than the characteristic bog species such as the *Sphagnum* moss. Areas of deep peat with dense heather and areas rich in lichens or non-*Sphagnum* mosses are often indicators of vegetation change due to drainage (Lindsay et al, 2014).

Areas of fen or poor fen vegetation indicate surface or groundwater flow lines, and are reported as potential routes for water ingress to the weaker catotelm peat. Such water ingress can, in combination with other factors, lead to peat instability.

4.6 Land Use

There are a range of land uses and activities occurring on blanket bogs and associated habitats, and some of the more relevant in terms of peat stability are discussed below.

4.6.1 Afforestation

Settlement of peat deposits has been recorded within forestry, likely due to the lowering of the water table due to the presence of drains and the effect of the growing tree crop (transpiration, etc.), both of which cause gradual drying of the peat mass over time. A study undertaken in Caithness, Scotland over a 50-year period showed a reduction in peat thickness of around 13% (500mm) within forested areas (Sloan et al, 2019), when compared to adjacent unforested areas. The rate of change was quickest in the first 30 years, with relatively little change noted after this time period.

Within forestry areas, forestry furrows and drains form preferential paths for water flow (Anderson, 2001). Evidence suggests that forestry furrow/drains, if deep enough, can restrict the growth of tree roots, limiting any potential stabilising effect of the root system on a peat slope. Such drains and furrows also damage the upper fibrous part of the peat (Acrotelm) which gives strength to the upper peat. There is also evidence that the presence of such drains and furrows can lead to cracking in the less fibrous and hence weaker peat (Catotelm) underlying the drain/furrow. This creates drainage paths at a lower level within the peat, which can lead to erosion and undermining of the peat mass (Anderson, 2001).

Hendrick (1990) details the impact of forestry plough furrows in relation to a bog flow at Bellacorrick, Co. Mayo, where heavy rainfall and a lack of suitable interceptor drains led to a failure.

A report by Lindsay and Bragg (2005) suggested that forestry row alignments, desiccation cracking and loading (by the plantation trees) could all influence peat stability.

Forestry activities have effects in common with drainage modifications, and these, alongside hypothesised effects are incorporated in Mills & Rushton (2023) which describes a risk-based approach to assessing baseline stability at a site-scale.

4.6.2 Drainage

Natural drainage and man-made drainage measures designed to control surface water flow and reduce the water content in the peat have been identified as a contributory cause of some peat failures. These drainage paths can allow the migration of surface water to a failure site therefore precipitating failure by focussing the flow of water into a localised area, which can lead to increased water pressure in the peat, as well as erosion of the surface of the peat.

In some instances, agricultural works led to the disturbance of an existing drainage network and eventually caused failure (Warburton et al, 2004).

Drains also damage the upper fibrous layer of peat (Acrotelm). In this case, man-made drainage channels are of more interest, as they are most readily identifiable from aerial photography.

As noted in Section 4.4 above, the (natural) drainage of an upland peat site will be altered by construction and their associated infrastructure, leading to accelerated water runoff and the potential for erosion (Natural England, 2010). This, in turn, may increase the risk of peat failures in areas where runoff is concentrated.

Drainage of peat leading to drying (and even the disappearance) of the acrotelm results in progressive loss of peat-forming conditions and peat-forming vegetation, which means that the acrotelm is no longer capable of providing fresh peat material to the catotelm. Many plant species which typically invade a dry acrotelm surface have root systems which further dry out both the acrotelm and the upper layers of the catotelm, thus enhancing the impact of the drains (Lindsay et al, 2014). Such degradation alters the normal ecohydrological functioning of the bog. It reduces the thickness of the protective vegetation cover and fibrous acrotelm over the weaker catotelm peat which in turn is likely to reduce the resilience of the peatland to other perturbation such as droughts, extreme rainfall events or land use pressures.

Where a blanket or raised bog is mechanically cut perpendicular to the contours this facilitates drainage of the bog and has also been noted to lead to increased erosion of the peat due to an increase in the rate of runoff (Large and Hamilton, 1991).

Where a bog is cut in various orientations this can cause water to be retained in the cuts and additional lateral loads being introduced into the bog. Water retention within mechanical cuts is reported to occur particularly where the orientation of the cuts is parallel to the slope contours (i.e. cuts are across the slope).

Mills & Rushton (2023) reported that most reports of peat slides and bog bursts (in Scotland) in association with drainage occurs where drains are oblique to slope.

The presence of peat pipes at the base of the peat has also been noted at several failure sites (Warburton et al 2004, Dykes and Warburton, 2007, Boylan et al 2008). Mills (2002) examined records of slope drainage for bog burst and peat slides reported in the literature and found a large proportion of the peat-slide failure sites had drainage direct into the heads of the failure.

4.6.3 Peat Cutting/Extraction

The mechanical cutting of peat by ‘sausage machine’ has been linked to several failures, such as at Tullynascreen townland, Co. Sligo (Alexander, 1985), Ballincollig Hill, Co. Kerry (Kane et al, 2019) and Glencolumcille, Co. Donegal (Figure 4.4) (Long, Jennings & Carroll, 2011). This technique vertically cuts the upper 1-1.5m of the peat, which can remove a significant proportion of the strength of the peat deposit. If this mechanical cutting is undertaken across a slope, the vertical cuts can open slightly, allowing the ingress of surface water. This water then builds up in the individual cuts, increasing the lateral pressure on the adjacent peat (Kane et al, 2019).

Peat extraction at the edge of a peat deposit typically results in an open unsupported peat face. This, over time, acts as a drain for the edge of the peat, drying the edge of the peat. Peat cutting may also increase the risk of peat mass movements such as bog slides because the peat bank constitutes a break in the fibrous vegetation mat which binds the bog system securely on a slope. Drainage offers the potential for cracks to develop in the peat, thus permitting heavy rainfall to reach and lubricate the junction between the peat and the mineral sub-soil (Lindsay, 2014). The failure at Knocknageeha in 1896 is considered to have been the result of cutting a relatively deep peat face, exposing the lower, softer, more humified peat which then failed.

Figure 4.4: Peat failure, Glencolumcille, Co. Donegal showing a peat failure within a machine cut area of peat. (Photo courtesy of Dr Paul Jennings)

4.6.4 Burning of Peat Bogs

Burning on peat bogs can lead to damage to peatland species, peatland habitat and peatland ecosystem functions. The loss of key bog vegetation can lead to erosion of the peat surface, drying of the near surface peat layers and possibly reduced water storage capacity within the peat due to the loss of vegetation. Burning of vegetation has been mentioned as a possible conditioning factor in failures at Carrowmaculla, Co. Fermanagh (Tomlinson, 1981) and Straduff, Co. Sligo (Alexander et al, 1985).

Bogs can be shown to exhibit an altered vegetation composition, structure, and growth-form due to fire 80 years or more after a fire event. If the surface has been burnt to the point where all living Sphagnum has been lost, for example, it may take more than 50 years for Sphagnum plants to return when burning has produced a bare peat surface. In terms of impacts, the short 'return times' associated with human-induced fires offer little prospect of full ecosystem recovery and tend to encourage 'fire-tolerant' species (such as heather) at the expense of other peatland species (Lindsay et al, 2014). The absence or alteration of surface vegetation would impact negatively on peat stability, specifically in terms of the ability to absorb rainfall, causing increased runoff.

4.6.5 Impacts of Grazing Animals

The damage caused by grazing is nearly always a long-term (decades) process. Ultimately it results in loss of peat forming vegetation and consequent drying out of the bog surface. In sensitive locations the end-result of persistent high stocking levels is that the acrotelm is lost completely, the drier surface is colonised by non-peat forming species, patches of bare peat appear, and as a consequence increases the erosion risk (Lindsay et al, 2014).

Animal tracks are indicated to form preferential pathways for drainage, possibly increasing infiltration and impacting negatively on stability. Localised compaction of the ground can also occur, as groups of animals often step in the same locations, however this effect is highly localised and is difficult to quantify (Winter, 2012).

Immediate ecosystem impacts are associated with physical damage to the vegetation and bog surface through trampling, grazing and urine/faecal returns. These include the creation of tracks and small areas of bare peat surface that can act as the focal points for erosion. Indirectly over the long term, there may be a reduction in the annual biomass that is retained in the living surface layer (both above and below ground). This may ultimately lead to a decline in the thickness of the acrotelm (Lindsay et al, 2014).

4.7 Construction on Peatlands

Sudden loading of the peat surface has been recorded as a trigger factor for peat failures in Ireland (Boylan et al, 2008, Kane et al, 2019), the UK (Giles & Griffiths, 2020) and in Canada (Hungr & Evans, 1985). Failure is initiated by a bearing type failure beneath the loaded area resulting in development of shear planes either within or along the base of the peat mass below the loaded area. The failed peat effectively loses strength and increases the active pressure on the peat downslope. This leads to a progressive failure of the peat down-slope and in some cases can lead to an escalating and runaway failure.

The use of upland blanket bogs, for example for the construction of wind farms, has also led to several peat failures. These are usually specifically linked to construction activities, such as Derrybrien (2003), Ballincollig Hill (2008) and Meenbog (2020), as well as more recently (during 2022) in the Shetland Islands.

It is also noted that the natural hydrology of an upland peat site will be altered by the construction of wind farms and their associated infrastructure (Natural England, 2010), which can impact on the peat stability/failure susceptibility of a site.

Loading of the peat surface was identified as a factor in the failure on Slieve Aughty (Derrybrien), Co. Galway in 2003 (AGEC, 2004). At this site, the placement of a relatively small load on the peat surface led to a failure involving 450,000m^3 of peat. It is thought that the failure was initiated by a bearing type failure beneath the loaded material which increased the active pressure on the peat down slope. This would have led to a progressive failure of the material down slope and a runaway failure.

4.8 Substrate Conditions

In the context of steeper hillslope peat failures, (iron) hard pan deposits forming hydrological barriers and potentially weak failure surfaces have been identified beneath thin blanket peat (Dykes and Warburton, 2007). The presence of an impermeable layer, such as a soft clay layer or iron pan, directly beneath peat can be a conditioning and triggering factor for the onset of a Peaty-debris slide (Warburton et al, 2007), but also applies to other failure types. This impermeable layer provides a sliding surface for the failure, with the peat often remaining relatively intact as it is transported. The impermeable layer also effects the water pressure within the peat deposits, especially following intense rainfall events.
Examples are noted in Alexander et al (1986), describing a failure near Geevagh, Co. Sligo, for a series of failures on Dooncarton Mountain, Co. Mayo in September 2003 (Dykes and Warburton, 2007), as well as at Flughland, Co. Donegal (Figure 4.5) (Jennings & Kane, 2019).

Figure 4.5: Base of Peat failure, Flughland, Co. Donegal, 2017.
(Photo courtesy of Dr Paul Jennings)

4.9 Anthropogenic Climate Change

From a review of published papers relating to peat failure, it appears that little or no dedicated research has been undertaken into the effects of anthropogenic climate change on peat stability. Winter (2013) has produced a report which discusses the potential change in hazard from climate change to landslide risk in relation to the Scottish landscape. This suggests the potential for greater landslide activity in terms of frequency and magnitude in Scotland. A study by Holden and Burt (2002) reviewed the potential for drought conditions to alter the hydrology of upland peat deposits, based on laboratory testing of peat samples. This indicated that drought conditions resulted in reduced surface runoff, increased infiltration, and more water flow deeper in the peat once rainfall occurred. The impacts of such a change on peat stability have not been examined.

Current climate models suggest that higher temperatures and generally drier summers can be expected due to anthropogenic climate change, along with an increase in the number of heavy precipitation events (Nolan and Flanagan, 2020). This, in theory, would lead to a drawdown in the water table during summer, altering the bog ecosystem. However, evidence from the peat archive indicates that drier conditions, and thus lower water tables, have occurred in the past and yet peat has often continued to accumulate even during these periods. This, however, appears to be linked to the presence of sufficient vegetation (as is present on intact blanket bog), which in many peat bogs no longer exists (Lindsay et al, 2014). The presence of artificial drainage, altering the type of vegetation present, may reduce the capacity of a peat body to resist the impact of changes in rainfall patterns. Dykes (2022) indicates that the highest frequency of failure events appear to occur in October/November, altered when compared to an earlier analysis by Alexander et al (1985), which indicated the highest frequency in December/January, possibly associated with higher autumnal rainfall following hot/dry periods.

4.10 Frequency of Conditioning and Triggering factors in Reviewed Literature

Scientific papers covering approximately 50 no. peat failure events (including clusters of failures as a single event) across Ireland and the UK have been reviewed. However, it is noted that this represents only a small percentage of the total number of peat failures that have occurred over the past 100 years (GSI national landslide database, 2024).

The table in Appendix A shows the conditioning and triggering factors for the reviewed publications on peat failures in Ireland and the UK and is based on works by Dykes (2008). Previous studies (such as Dykes, 2008) have shown that certain patterns of conditioning and triggering factors can be associated with different types of failures. A significant proportion of the failures were also associated with breaks in slope, both concave and convex. Heavy rainfall is the most highlighted trigger; however, it is clear, that a peat failure also requires a combination of pre-existing site-specific risk factors as otherwise peat failures would be more widespread were rainfall/intense rainfall be the only factor involved. All significant site-specific risk factors may not have been investigated for many of the peat failures documented in the reviewed publications.

Table 4-2: Frequency of Conditioning and Triggering Factors

Conditioning and triggering factor	Conditioning Factor											Trigger	
	EP	FD/DD	PC/PE	PL	CV	CX	HA	LA	MS	SP	PB	HR	HI
Occurrence in literature	2	11	12	5	13	21	12	11	8	7	6	34	5

Note - EP: Eroded Peat, FD/DD: Forestry drain/drainage ditch, PC/PE: peat cutting/excavation, PL: peat loading, CV/CX: concave/convex slope, HA/LA: High/low antecedent rainfall, MS: mineral soil, SP: soil/peat pipes, PB: peat bank, HR: heavy rainfall, HI: human impact (direct trigger from a specific activity, such as construction works).

Of the 51 no. failure events in the reviewed literature rainfall was identified as a trigger in 34 cases (66%) of these, with direct human impact (such as construction) specifically mentioned in 5 cases (10%), with the remainder unknown.

As stated earlier, peat failures are unlikely to be initiated as a result of one factor alone. Rather, it is usually a combination of factors that contributes to a failure. While intense rainfall is reported as a trigger in 66% of the cases reviewed, these failures must involve other contributory or predisposing factors, as otherwise every heavy rainfall event would cause numerous, significant peat slides across Ireland.

A number of the conditioning factors in the table above could be grouped together as land use/human impact factors:

- forestry drain/drainage ditch (FD/DD),
- peat cutting/peat excavation (PC/PE),
- peat loading (PL), including construction loading,
- presence of peat banks (PB)

A summary of the frequency of these factors in the revised peat failures is shown in Figure 4.6. As most failures have multiple conditioning factors, the total percentage adds up to greater than 100%. **Importantly this shows that land use, along with break in slope, are significant conditioning factors for peat failures.**

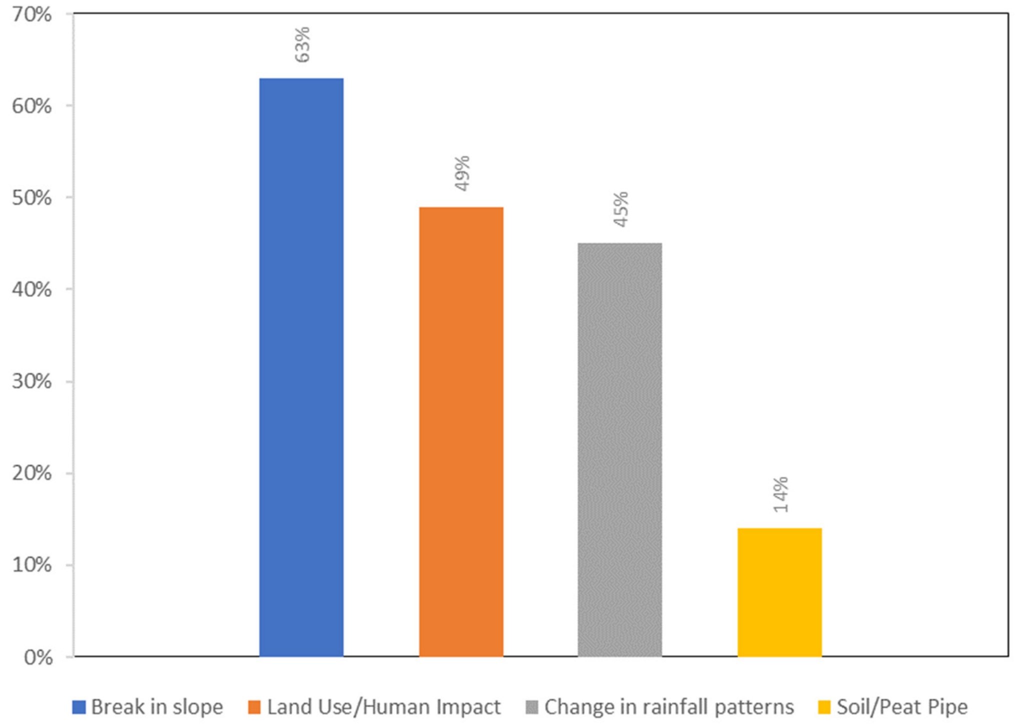

Figure 4.6: **Frequency of Conditioning Factors in Peat Failures**

Combinations of two or more factors, such as convex slope, high antecedent rainfall and heavy rainfall are recorded in five of the reviewed failures (all three factors recorded). Looking purely at combinations involving rainfall:

- Combination of convex slope and heavy rainfall – 15 times from 21 references to convex slope (30% of total failures reviewed).
- Concave slope and heavy rainfall – 8 times from 13 references to concave slope (16% of total failures reviewed).
- Peat cutting/excavation and heavy rainfall – 10 times from 12 references to peat cutting (18% of total failures reviewed).
- Low antecedent rainfall and heavy rainfall – 9 times from 11 references to low antecedent rainfall (18% of total failures)
- High antecedent rainfall and heavy rainfall – 11 times from 12 references to high antecedent rainfall, conditioning and triggering factors in 22% of total failures reviewed.
- Human impact and heavy rainfall – 11 times from 22 references to human impact as a conditioning factor, 22% of total failures reviewed.

4.11 Conditioning and Triggering Factors for peat failure types

The table below summarises, in general terms, the main conditioning factors referenced within the literature reviewed in relation to the type of peat failure. Land use/human impact triggers are also highlighted in blue. This is presented in general terms, as there can be variation in conditioning/trigger factors for peat failures.

Table 4-3: Conditioning and Triggering Factors for peat failure types

Failure Type	Conditioning and Triggering Factors
Bog bursts/flows	Rainfall, peat strength, land use, convex break in slope (Bog flows), human impact: removal of peat banks (lateral support)
Bog slides	Rainfall, peat strength, land use, presence of highly humified peat, break in slope, human impact: machine cutting of peat, peat loading
Peat slides	Rainfall, break in slope, land use, human impact: change in drainage pattern, peat loading
Peaty-debris slides	Rainfall, steep slopes, impermeable layer below peat
Peat flows	Rainfall, human impact: peat loading

Summary

A number of papers have been reviewed detailing peat failures across Ireland and the UK. These papers provide a wide range of conditioning and trigger factors for peat failures.

An overview of the different types of peat failure based on Dykes and Warburton (2007a) is provided.

Peat failures are divided into six different types of failures, namely: bog burst, bog flow, bog slide, peat slide, peaty-debris slides and peat flows.

A summary of the main conditioning and triggering factors, where identified in the literature review, is provided.

Factors such as the physical characteristics of the peat (such as strength), subsoil conditions, land use, hydrological conditions and geomorphology have all been identified as conditioning factors for peat failures.

The most commonly reported trigger factors for failures were direct human activity (such as construction) and intense rainfall events.

It should be noted that based on the publications reviewed, it is rare that one individual factor alone is reported to initiate a peat failure. This suggests that it requires a combination of two or more factors at the same location to initiate a peat failure, irrespective of the type of failure. Commonly reported factors are topography; peat properties; human, activity or land use at the site; and rainfall.

The land use history of a peatland is a significant conditioning factor for peat failures, with numerous peat failures recorded either within areas of forestry plantation or along the edge of such plantations, where the forestry plantation has altered the natural condition and hydrological functioning of the peatland. Land use also extends to agriculture, peat excavation/peat cutting and loading of peat.

From a geotechnical perspective, the most important factors in peat stability, as reported in the literature reviewed for this study, are considered to be peat depth, peat strength, peat permeability, break in slope and the morphology of the base of the peat (Boylan et al 2008, Dykes and Jennings 2011, Dykes and Warburton, 2007b).

With regard to hydrology and hydrogeology, the drainage of peat, both natural and man-made, is considered to be a highly important factor in the stability of a peat deposit. Peatland vegetation, peat soil, and peatland hydrology are inextricably interlinked and modification of one affects the other two in a complex feedback loop. Natural peatland vegetation creates the peat and is also an important factor in regulating the hydrological regime of the peatland.

The presence of structures such as peat pipes located at the base of a peat deposit has been linked to several peat failures. Peat pipes can allow water to access the deeper weaker catotelm peat layers or the peat /sub-peat interface which can instigate failure. These peat pipes can form either naturally or as a result of artificial drainage.

The most common reported trigger factor within the reviewed peat failures was rainfall. This rainfall can either be an intense, short term rainfall event or a prolonged period of higher-than-average rainfall. However, such rainfall appears to require a range of conditioning factors, several specifically linked to peatland ecohydrology and ecosystem functioning, to trigger a failure.

A summary of the conditioning and triggering factors associated with the different types of failures reviewed is also provided. A combination of such conditioning and triggering factors is required for a peat failure to occur even though rainfall is the one triggering factor that is reported within the literature for each failure type.

This summary is based on analysis of the failures listed in Appendix A.

Failure Type	Conditioning and Triggering Factors
Bog bursts/flows	Rainfall, peat strength, land use, convex break in slope (Bog flows), removal of peat banks (lateral support)
Bog slides	Rainfall, peat strength, land use, presence of highly humified peat, break in slope, machine cutting of peat, peat loading
Peat slides	Rainfall, break in slope, land use, change in drainage pattern, peat loading
Peaty-debris slides	Rainfall, steep slopes, impermeable layer below peat
Peat flows	Rainfall, peat loading

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Appendix A

Summary of Peat Failures

Location	Type	Year	Conditioning Factors											Trigger		
			EP	FD/DD	PC/PE	PL	PB	CV	CX	HA	LA	MS	SP	HR	UN	HI
Lough Boleynagee, Co. Mayo	BF	1932					Y		Y	Y			Y		Y	
Maghera, Co. Clare	BF	1934							Y					Y		
Glendun, Co. Antrim	BF	1963						Y		Y				Y		
Barnesmore, Co. Donegal	BF	1963			Y			Y						Y		
Carrowmaculla, Co. Fermanagh	BF	1979							Y	Y				Y		
Tullynascreen, Co. Sligo	BF				Y				Y	Y				Y		
Straduff, Co. Sligo	BF	1984							Y		Y	Y		(Y)		
Maghera, Co. Clare	BF			Y					Y						Y	
Slieve Bloom, Co. Laois	BF	1988		Y					Y						Y	
Conaghra, Co. Mayo	BF			Y			Y		Y						Y	
Meenacharvy, Co. Donegal	BS	1946	Y		Y				Y					Y		
Slieve Rushden, Co. Cavan	BS	1965			Y				Y	Y				Y		
Bellacorrick Forest, Co. Mayo	BS	1988		Y				Y			Y					
Skerry Hill, Co. Antrim	BS	1991						Y			Y			Y		
Carntogher, Co. Derry	BS	1993	Y					Y		Y			Y	Y		
East Cuilcagh, Co. Cavan	BS	1986					Y	Y							Y	
East Cuilcagh, Co. Cavan	BS	1992					Y	Y						Y		
East Cuilcagh, Co. Cavan	BS	1996					Y	Y							Y	
Slieve Bloom, Co. Offaly	BS	1973							Y						Y	
Cuilcagh, Co. Fermanagh	PS	1986								Y		Y		Y		
Dooncarton Mountain, Co. Mayo (9)	PS/PDS	2003							Y		Y	Y	Y	Y		
Slieve-an-Orra, Co. Antrim (7)	PDS	1980		Y	Y			Y	Y	Y		Y		Y		
Slievenakilla, Co. Leitrim (2)	PDS	1986						Y	Y		Y	Y		Y		
Cuilcagh, Co. Fermanagh	PDS	1998									Y	Y	Y	Y		
Cuilcagh, Co. Fermanagh	PDS	2000									Y	Y		Y		
Slieve Bearnagh, Co. Clare	PF	2003		Y	Y	(Y)		Y								
Sonnagh Old, Co. Galway	PF	2003		Y	Y				Y							
Derrybrien, Co. Galway	PS	2003		(Y)		Y		(Y)			Y					Y
Carrane Hill, Co. Sligo (8 slides - Corrie Mountain, Geevagh, Derrysallagh)	PS/BS	2008							Y					Y		
Ballincollig Hill, Co. Kerry	PF	2008			Y	Y								Y		Y
Flughland, Co. Donegal (8 slides)	PS	2017										Y		Y		
Croaghan, Co. Antrim	BF	2014											Y	Y		
Clare Island	PS	2007						Y						Y		
Silsean, Co. Wicklow	PS	1937							Y							
Kilbride, Co. Wicklow	PS	1995											Y			
Knocknageeha, Co. Kerry	BB	1896			Y					Y				Y		
Glencolmcille, Co. Donegal	PS	2009			Y									Y		
Meenbog, Co. Donegal	BF	2020		(Y)		Y			Y	Y						Y
Shass Mountain, Co. Sligo	BS	2020		Y							Y			Y		
Mount Eagle, Co. Kerry	BS	2020		Y						Y						
Hart Hope, England	PS	1995							Y					Y		
A5 Llyn Ogwen	PDS	2005					(Y)		Y					Y		
Shetland Islands	PS	2003												Y		
Glen Ogle, Scotland	PDS	2004							Y	Y				Y		
Isle of Lewis, Scotland	BF	1959												(Y)		
Teesdale/Weardale (5 slides)	PDS	1983									(Y)		Y	Y		
Glen Dochery, Wester Ross, Scotland	PDS	2015								Y				Y		
Prince Rupert, British Columbia	PF	1982				Y										Y
Wingecarribbee Swamp (NSW, Austrialia)	BF	1998			Y									Y		
La Vraconne, Switzerland	BF	1987			Y						Y			Y		
Lake Northern Puttjern, Norway	BS	1997														Y

BF	Bog flow/burst
BS	Bog slide
PS	Peat slide
PDS	Peaty-debris slide
PF	Peat flow
EP	Eroded Peat
FD/DD	Forestry Drain/Drainge Ditch
PC/PE	Peat cutting/extraction
PL	Peat loading
CV	Concave brake in slope
CX	Convex break in slope
HA	High antecedent rainfall
LA	Low antecedent rainfall
MS	Mineral soil substrate
SP	Soil/Peat pipe
PB	Peat Bank
HR	Heavy Rainfall
UN	Unknown
HI	Human Impact - specific trigger event
🟨	Cells highlighted in yellow are considered to be caused by human action

*Note – Expanded from Dykes (2008b)