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An all-island landslide database for Ireland

Cullen, N.D.[1] and Bourke, M.C.[2]*

[1] Department of Geography, School of History and Geography, Dublin City University, Ireland.

[2] Department of Geography, School of Natural Sciences, University of Dublin, Trinity College, Ireland.

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Abstract: National landslide inventories are essential for effective landslide hazard assessment, risk management, and adaptation to climate change. The island of Ireland currently has two separate inventories compiled independently by the Geological Survey of Ireland and the Geological Survey of Northern Ireland. However, the physical properties that predispose a slope to failure e.g. slope, material type, drainage and land use, extend across the political border. Likewise, the climatic factors that trigger landslides, particularly prolonged and/or intense rainfall, affect the island as a whole and are not restricted to a single jurisdiction. Maintaining separate inventories creates an artificial division in the landslide record. A single database provides a more complete and consistent record, supporting improved hazard assessment and evaluation of slope response to climate change.

We present the methodology for the compilation of the first all-island landslide database. We use the two previously assembled jurisdictional databases supplemented with our own data.

The new all-Ireland landslide inventory contains 3,098 landslides, including 134 previously unreported events. Weather data were also added to 86 landslide events recorded in the Geological Survey of Ireland's National Landslide Database. The all-Ireland landslide database contains the earliest written landslide record documented globally. There is the potential to extend and enhance the inventory through further analysis of historical sources. We find that the number of failures listed in coastal locations are significantly under-reported. A preliminary analysis of the database indicates that most slope failures in Ireland occur in peat (45%) and 95% of those are associated with wet conditions. This is significant given the projected changes in climate.

Keywords: *landslide, inventory, peat, geomorphology*

*xxxxxxxxx (Corresponding Author)

1. Introduction

Landslides are defined as the movement of a mass of rock, debris or earth down a slope (Cruden, 1991; Hungr, Leroueil and Picarelli, 2014). They encompass a range of gravity-driven processes including falls, slides, flows and complex failures that combine two or more these mechanisms (Varnes, 1978; Hungr, Leroueil and Picarelli, 2014). In Ireland, many landslides occur in peat (Bourke and Cullen, 2024). The prevalence of peat failures in Ireland has led to a formal classification scheme including peat slides and bog flows, reflecting their distinct material properties and failure mechanisms (Dykes and Warburton, 2007). Irish landslide inventories record events ranging from small, localised failures to larger and more complex slope movements in peat, soil, and rock. They occur across a range of geomorphological settings including upland slopes, coastal cliffs and slopes modified by human activities such as road and construction cuttings (Herrera *et al.*, 2018; Martinović *et al.*, 2018; Geological Survey Ireland, 2022). This diversity of landslide types, materials, magnitudes and settings highlights the importance of systematic inventories that can document spatial and temporal patterns of slope failure.

At the global scale, landslide inventories contribute to understanding broad spatial patterns of slope instability and potential links with climatic variability (Guzzetti *et al.*, 2012; Gariano and Guzzetti, 2016). However, robust analysis of landslide frequency trends and attribution of triggering mechanisms requires coordinated inventory development at regional scales, where climatic drivers and geomorphological conditions are broadly comparable (Wood *et al.*, 2020). In Europe, efforts to harmonise landslide databases have highlighted the importance of consistent reporting standards and long-term records for detecting potential climate-related trends (Herrera *et al.*, 2018). Ireland forms part of this broader European framework. At national scale, inventories must adopt a pragmatic minimum threshold. Other inventories apply the principle of 'substantial completeness' (Guzzetti et al., 2012; Wood et al., 2015), whereby databases are considered reliable above a threshold where events can be consistently detected and recorded. This typically excludes the smallest failures, which are difficult to observe systematically and add little to long-term trend analysis.

Landslide inventories for Ireland are currently maintained separately by the Geological Survey of Ireland (GSI) and the Geological Survey of Northern Ireland (GSNI), creating inconsistencies in coverage, classification and reporting across the island. Developing a coherent all-island inventory strengthens regional comparability, improves national-scale hazard assessment, and provides a baseline for evaluating potential changes in landslide activity under future climate change. Here we (1) describe the methodology used to construct the all-Ireland inventory (A-II); (2) present a preliminary analysis of the slope materials involved in recorded failures; (3) examine the weather conditions associated with these events and (4) discuss opportunities to enhance and extend the inventory through integration of additional historical, archival and environmental data sources.

2. The existing Irish Landslide Inventories

This section outlines the structure, content and key attributes of the two existing landslide inventories for Ireland, highlighting similarities and differences relevant to their integration.

The movement-style categories used in both databases broadly correspond to established landslide classification frameworks (e.g. Varnes, 1978; Hutchinson, 1988; Hungr, Leroueil and Picarelli, 2014).

The GSI National Landslide Database (NDL) is structured as a vector dataset comprising point and polygon features that record information on the date of occurrence (where known), location, material type, slope characteristics and other associated attributes for events recorded up to 2020 (Geological Survey Ireland, 2022). In some cases, the date of failure is uncertain or recorded as a range rather than a specific day. The inventory draws on a diverse range of sources, including remote sensing mapping supported by field validation (Bourke and Pilla, 2014; McKeon, 2016), archival records such as the Irish Annals, peer-reviewed publications and media reports.

The GSNI inventory draws on comparable source materials, but it does not include a mapping campaign. It uses a code-based schema to record movement style, dominant material, slope characteristics and associated attributes, including indicators of spatial and temporal precision. The GSNI database records slope and environmental condition attributes but does not contain a dedicated field for weather conditions at the time of failure. In addition the inventory stops at 2016 but is currently being updated e.g. the Atlantic Geohazard (AGEO) Risk Management project.

Neither database has a dedicated category for antecedent weather or event weather conditions. References to weather are generally restricted to descriptions of extreme weather e.g. 'heavy rainfall', '80mm of rainfall' or 'dry summer followed by intense rainfall' under the heading 'Trigger' (GSI) or general 'Comments' (GSNI).

Both inventories contain fields related to landslide dimensions (e.g. length, width, depth or estimated area), but these attributes are incompletely populated and are not consistently recorded across events.

Coastal landslides are largely absent from the GSI NLD and are not clearly distinguished within the GSNI dataset. Given that approximately 1,288 km of Ireland's coastline is cliffed (Barron *et al.*, 2011) and subject to landslides in rock, sand and Quaternary sediments, this represents an important area for future inventory development.

While both inventories document landslide occurrence and key event characteristics, they differ in schema structure, classification conventions and attribute recording formats, which requires careful reconciliation for direct comparison and integration at the island scale. For example, in relation to slope material, the GSNI schema does not include a discrete 'earth' category. As a result, it is not possible to distinguish between failures occurring in earth and those occurring in debris within the GSNI dataset in the same way as in the GSI NLD.

The Construction of the all-Ireland Inventory (A-II)

An all-island landslide database was compiled using both historical documentary sources and contemporary records, following the principle that long-term, systematically assembled inventories are necessary to examine landslide occurrence across temporal scales (Wood et al., 2020). In building and blending the database, we use:

1. An unpublished version of the NLD from the GSI of landslides up to and including 2019 for the Republic of Ireland (McKeown 2019).
2. The online NDL which contains additional landslides up to 2022 (Geological Survey Ireland, 2022)
3. The GSNI landslides database (Parker, Geological Survey of Northern Ireland, pers. comm., 2022).
4. Analysis of available sources to
   - **(a)** Confirm details,
   - **(b)** Collate additional or missing information on weather conditions at the time of the landslides event(s) and
   - **(c)** Update the inventories to June 2022.
5. Independent Research: For older manuscripts not available online, we visited libraries to confirm the date of the event and record any additional environmental information not currently held in the GSI NLD and GNSI databases. For example we consulted the Praeger (1897) volume which is held in the National Library of Ireland. In addition, we used unpublished data from Dr K. Hickey that included his observations of landslides from historical sources, including the 1851 Irish census and Lowe (1870). For more recent manuscripts, we conducted a literature search using the Google Scholar platform. Our search of the grey literature consisted predominantly of online reports produced by government agencies and local council. Finally, we undertook an online search of newspaper articles and mentions of landslides on the social media platform X (formerly Twitter).

For online searches, we used a defined set of terms corresponding to recognised landslide types (Table 1). These terms were aligned with established classification frameworks, including Hutchinson (1988), widely applied in UK and Irish practice; Varnes (1978) and Hungr et al. (2014) to ensure international comparability; and Dykes and Warburton (2007) for peat-specific failures. The use of consistent terminology ensures that the all-Ireland inventory is scientifically robust and comparable to other national and international databases. However, we note that not all events can be classified with certainty. Early historical accounts often lack sufficient detail to determine movement type or material involved. In such cases, events were entered as ‘unclassified’ in the database to maximise inclusivity while maintaining transparency.

Search term	Corresponding classification term	Classification system
Landslide	Landslide (general category)	Hutchinson (1988)
Slope failure	Unclassified landslide	Hutchinson (1988)
Bog burst	Peat slide / Bog flow	Dykes & Warburton (2007)
Peat slide	Peat slide	Dykes & Warburton (2007)
Rockfall	Rock fall	Hutchinson (1988); Varnes (1978)
Rockslide	Rock slide	Hutchinson (1988); Hungr *et al.* (2014)
Mudslide	Earth flow / Mudflow	Hutchinson (1988)
Earth flow	Earth flow	Hutchinson (1988)
Debris flow	Debris flow	Hutchinson (1988); Varnes (1978)
Rotational slide	Rotational slide	Hutchinson (1988)
Translational slide	Translational slide	Hutchinson (1988)

The historical imagery function in Google Earth Pro was used to verify newly reported landslides. Systematic review of time-series imagery during this process also resulted in the identification of additional, previously unrecorded landslides, consistent with the remote-sensing approach adopted by Bourke and Pilla (2014).

Initial landslide database analysis:

The all-island landslide database (A-II) was analysed to examine landslide occurrence by material type and associated weather conditions. Records were filtered to include only events where material type was specified (e.g. rock, peat). Similar material categories were combined where appropriate; for example, 'peat' and 'peaty soils' were grouped together, as distinctions between these categories in the GSI and GSNI databases are descriptive rather than consistently aligned with the refined peat classification proposed by Dykes and Warburton (2007). This approach reduced unnecessary category proliferation while retaining the significance of peat-related failures.

The categories 'earth' and 'debris' were retained separately, as they are recorded as distinct material types within the source databases and could not be reliably reconciled. Overall, material type was specified for 1,201 landslides, representing 38.8% of the total inventory.

We subsampled data base for landslides events where the material is recorded to identify landslides where the approximate date was known (n = 497). Those events were again subsampled to extract events where weather conditions were available.

3. Results

The temporal distribution of landslides recorded in the inventory is strongly biased toward recent centuries (Fig. 1). Although the record extends back approximately four millennia, only a small number of early events are documented. The apparent increase in landslides since the eighteenth century likely reflects increased reporting and documentation rather than a true increase in landslide occurrence.

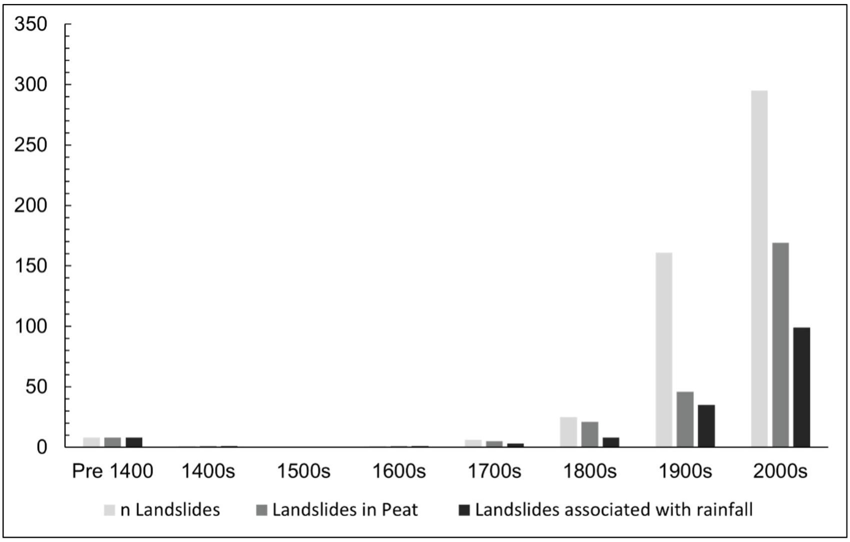

Figure 1. Temporal distribution of landslides recorded in the all-Ireland inventory for landslides where the date and material type is recorded. Bars show the number of recorded landslides per century (n), including total landslides (light grey), landslides occurring in peat (medium grey), and landslides associated with rainfall (black).

The unpublished GSI database contained records of 2,805 landslides (McKeown, Geological Survey of Ireland, pers. comm., 2019) while the publicly available online version listed 2,811 events (Geological Survey Ireland, 2022). The GSNI database included 177 reported landslides (Parker, Geological Survey of Northern Ireland, pers. comm., 2022). Duplicate entries between databases were identified through comparison of locations, event dates and descriptive attributes, and were reconciled to retain a single representative record for each unique landslide. In addition, our independent search for previously undocumented landslides identified 134 further events. The resulting unified all-Ireland database contains 3,098 unique landslides (Bourke and Cullen, 2024).

The frequency of landslide by material type is shown in Figure 2. Our data show that the most frequently reported landslide occurs in peat (45%). This is followed by earth (20%), debris (20%), rock (13%), and mud (2%).

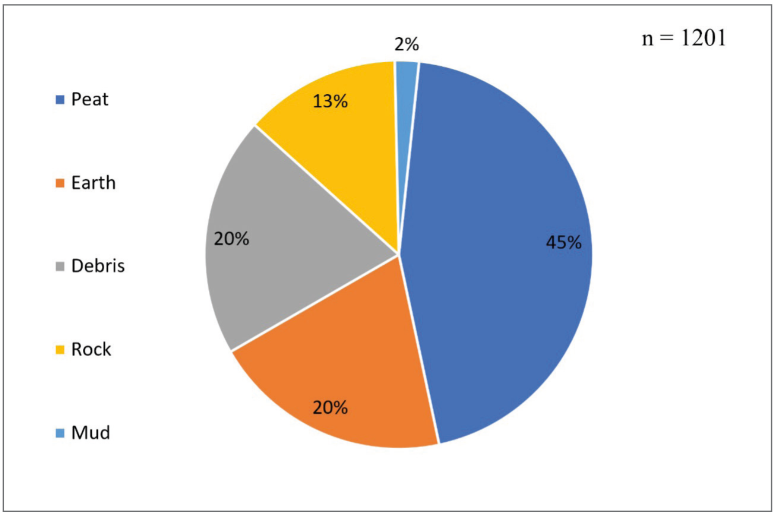

Figure 2. The distribution of landslides per source material in A-II

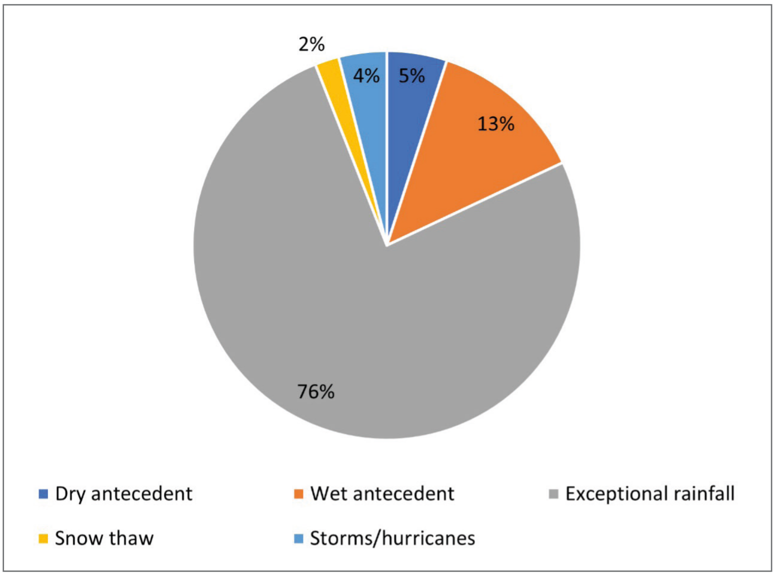

Figure 3: Weather conditions reported for landslides in all-Ireland database (n=163).

The A-II database contained 163 landslides that had weather conditions and material type indicated. The analysis shows that 76% of these landslides are associated with ‘heavy or excessive’ or ‘extreme’ rainfall. When peat landslides were specifically examined (n=107), 93.5% were associated with wet conditions.

Discussion and summary:

Analysis of landslides for which material type was recorded indicates that peat accounts for 45% of classified events. This proportion is consistent with previous studies of Irish landslides (e.g. Mouchel, 2011; Martinović, Musiał and Dim, 2016). Reported triggers indicate a strong association with heavy rainfall, with 94% of peat landslides linked to documented heavy rainfall events where trigger information was available. These findings provide context for ongoing work examining potential changes in landslide occurrence under future climate scenarios (Cullen and Bourke, In review).

Coastal landslides are not systematically identified as a distinct category within the GSI NLD and are not clearly distinguishable within the GSNI dataset. Consequently, coastal slope failures cannot be reliably extracted from the existing inventories. We note that failures on rocky substrates are significantly underreported, largely due to the absence of a coastal landslide inventory. For example, Cullen (2019) monitored an 800 m section of cliff at Ballard Bay, western Ireland, and recorded 540 rockfalls in a single year, with volumes ranging from 0.001 m^3 to the largest 11.56 m^3 which is included in A-II. While this study highlights the frequency of small-scale failures, volumes as low as 0.001 m^3 are unrealistic for inclusion in a national database, as thousands of such micro-failures may occur annually and are rarely recorded. At national scale, inventories must adopt a pragmatic minimum threshold. At the same time, management and adaptation to current and future coastal hazards will require the development of a dedicated coastal landslide inventory and sustained monitoring of rocky coasts.

Wood *et al.* (2020) discuss differences between long-term documentary inventories and systematically mapped event-based inventories for building landslide inventories that will assist in climate change attribution and mitigation. Historic landslide inventories represent the sum of numerous landslide events over (up to) thousands of years (Malamud *et al.*, 2004; Korup and Clague, 2009; Guzzetti *et al.*, 2012; Wood, Harrison and Reinhardt, 2015). Systematically mapped event-based inventories record directly observed landslides immediately after they occur, and mapping of the failure. These higher resolution data are a superior resource for a more robust analysis of magnitude-frequency relationships and the spatial patterns of landslides. It is also suggested that to determine the rainfall threshold, the precise time and day to should be recorded (e.g. Segoni, Piciullo and Gariano, 2018).

Where the concern is to understand the role of climate change Wood et al (2020) suggest that a database for climate change should be a long-term (>30 years) and a 'substantially complete inventory' (see Wood, Harrison and Reinhardt, 2015 for discussion of substantial completeness). Ireland has a wide range of potential data sources that could help address this need.

Natural archives

Reliable global climate records only began in the 1880s. Paleoclimate proxies provide the only means for determining past climatic patterns, extending back several thousand years. These preserved physical characteristics of the environment enable scientists to reconstruct climatic conditions over a time than instrumental records allow. In the fields of Quaternary science and Archaeology, the analysis of sediments and sedimentary facies often yield evidence that is used to reconstruct paleo-environmental regimes (including temperature and precipitation). Some facies preserve evidence of past floods and landslides.

The oldest, dated, landslide in Ireland is reported in an account of an archaeological excavation (Murray, 1997). Evidence of a bog burst was found below the excavated platform which was dated to around 4200 yr BP. At another site, detailed stratigraphic mapping and dating of industrially mined peat exposures by Caseldine and Geary (2005) indicate five raised bog bursts (BC 2200; BC 1250; BC 820; BC 600; BC 100) and two probable events (one of which is dated to AD 500). At a third site, a series of 3 bog bursts have similar ages (c. 3140, c. 2510 and c. 1540 cal. BP (Stastney, Young and Branch, 2018). While the above are included in the A-II database, there are potentially other landslide events in the archaeological and geomorphological record that have not been reported.

Natural proxies, such as tree-ring records, have been used to reconstruct past hydroclimatic variability, including prolonged wet and dry periods (St. George, Hefner and Avila, 2020). While such proxies provide valuable seasonal to annual-scale moisture reconstructions, they do not offer precise event-level timing of individual slope failures. Nevertheless, Irish oak chronologies remain under-explored in this context (Adelman and Ludlow, 2014) and may offer potential for identifying periods of heightened hydroclimatic variability (Cook e*t al.,* 2015) relevant to landslide occurrence. Although such proxies do not record individual landslide events, integrating proxy-derived hydroclimatic reconstructions with dated palaeo-landslide evidence may provide a basis for exploring long-term relationships between rainfall variability and landslide occurrence.

Historical Documents:

Ireland has a rich documentary record which has been utilised in the GSI and in this study, however a further review may reveal significant hitherto unreported landslides.

The Annals are considered as being among the most important sources for Irish history. They were recorded in monastic communities and contain lists of events (including ecclesiastical, secular and climatic) that run from AD 650 to1600 that include the 'middle ages' (A.D. 476 to A.D. 1450). They are considered by some as the first citizen scientists (Roche *et al.*, 2021). They have been effectively used in environmental studies e.g., to test the link between cold climatic events in Ireland and volcanic eruptions (Ludlow *et al.*, 2013). There are many references to landslides in the Annals. Indeed, we find that the first documented record of a landslide anywhere in the world is contained in the Annals. It describes a bog burst in 1488 (recorded in Kinahan, 1897; and cited in Feehan *et al.*, 2008). At that time mystical elements dominated people's understanding of natural processes and accordingly, the event was attributed to a supernatural wind created by fairies. The earliest scientific report of a landslide in Ireland was of a bog burst near Charleville, Co Limerick on June 7th in 1967 (Molyneux, 1697). Index entries from the Tables of Deaths in the 1851 Census of Ireland in, have revealed a series of landslides with details of year, location, source area, inundation area, and dynamics

One example from 1713 (March 10th) is as follows:

> *"Sinking of a Hill. Clogher, Ireland, 4 3/4 acres, probably owing to the constant great rains last Autumn and Winter - Bishop of Clogher, F.R.S." (Lowe, 1870).*

The potential documentary and instrumental records that could provide useful data for Ireland were recently reported to number around 750 (Mateus, 2021). Many of these pre-1850 sources are the focus of data rescue projects. One notable outcome is the production of the longest continuous monthly precipitation record available globally (1711–2016; Murphy *et al.*, 2018). These documents record meteorological conditions in all seasons, as well as singular extreme events, often at high temporal and spatial resolutions. They can therefore inform not only past climate reconstructions but also the interpretation of historical landslide events.

We note that these sources may exhibit biases (e.g. preferential reporting of extreme events) and coverage may be discontinuous. However, their greatest value lies in strengthening the landslide inventory. By linking descriptions of slope failures in historical accounts with independent records of extreme rainfall, floods, or prolonged wet conditions, it may be possible to infer plausible triggering mechanisms for landslide events lacking direct meteorological documentation. This enhances the completeness and interpretive value of the inventory and is consistent with recommendations that long-term databases integrate diverse archives to support climate change detection and attribution (Wood *et al.*, 2020). A comparable approach was demonstrated by Foulds et al. (2014) who combined documentary and geomorphological evidence to reconstruct a 250-year record of floods and related geomorphic events in Wales.

Historical documents can also directly record the impact of landslides. For example, Lowe (1870) described a bog burst in Clogher in 1713 that displaced nearly five acres of land. While in 1745 a most violent rainstorm near Dunmore, County Galway, where "A most violent and surprising rain in the neighbourhood of Dunmore, county of Galway, caused ten acres of bog to move from its original locality, and cover an adjoining meadow; and a neighbouring river formed a "lake of nearly fifty-five acres" (Lowe, 1870). Such accounts provide information on timing, location, source area, inundation area, and in some cases, the social and economic consequences.

Additional Irish sources with potential include the Schools' Folklore Collection 1937–1939 (Irish Folklore Commission, 1937), which documents extreme events such as the oldest known hurricane to impact Ireland (Oíche na Gaoithe Móire, January 1839), and the Ordnance Survey Name Books 1824–1846 (Ordnance Survey of Ireland, 1824), which provide all-Ireland descriptions of soils and topography. Although historical accounts may vary in detail, they can allow us to extract key attributes that can be entered into the landslide inventory, including climate related triggers. We recommend that the potential of these historical resources be further explored for enhancing the national landslide inventory.

The archaeological evidence, documentary archives and historical meteorological records describe above highlight the potential for developing a longer-term perspective on landslide activity in Ireland. When considered alongside systematic modern mapping, these sources can provide additional temporal depth and spatial coverage to the landslide record.

Effective landslide risk management across the island requires coordination between the two jurisdictions. Our recommendation comes at a time when cross-border management is challenged by changes in legislation. Until recently, most environmental policy and legislation in the Republic of Ireland, Northern Ireland, and the UK, was governed by legal frameworks of the European Union. The exit of the UK from the European Union complicates cross border management. In this context, maintaining consistency in landslide classification and reporting practices becomes particularly important.

The A-II database remains constrained by incomplete material classification, variable temporal precision and gaps in spatial coverage, including limited identification of coastal failures. While it represents an important first step towards a coherent all-island inventory, further systematic data collection, standardisation and documentation will be required to approach the level of completeness recommended for climate attribution studies (Wood *et al.*, 2020). Given projected changes in precipitation patterns under future climate scenarios, improved documentation of precise event timing and associated meteorological conditions would strengthen the capacity of the inventory to support rainfall threshold analysis and climate attribution. Nevertheless, establishment of a unified inventory provides an improved foundation for analysing landslide occurrence across the island.

Statements and Declarations:

Each of the authors confirms that this manuscript has not been previously published and is not currently under consideration by any other journal. There are no financial or non-financial interests that are directly or indirectly related to this work that would represent a conflict of interest.

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Author contributions:

All authors contributed to the study conception and design. Material preparation, data collection and analysis were mostly undertaken by NC. The manuscript was written by MB and NC. All authors read and approved the final manuscript.

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