BGS DIGITAL

User Guide: BGS Debris Flow Susceptibility Model for Great Britain (version 6.1)

Open report OR/22/023

British Geological Survey

BRITISH GEOLOGICAL SURVEY

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User Guide: BGS Debris Flow Susceptibility Model for Great Britain (version 6.1)

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The British Geological Survey is a component body of UK Research and Innovation.

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Foreword

The British Geological Survey (BGS) is a world-leading geological survey, focusing on public-good science for Government and research to understand earth and environmental processes.

We are the UK's premier provider of objective and authoritative geoscientific data, information and knowledge to help society to:

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Our products are supported by stakeholder focus groups, identification of gaps in current knowledge and policy assessments. They help to improve understanding and communication of the impact of geo-environmental properties and hazards in Great Britain, thereby improving society's resilience and enabling people, businesses, and the government to make better-informed decisions.

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Contents

Foreword i

Acknowledgments i

Contents ii

Summary iv

1 Introduction 5
- 1.1 Background to the dataset 6
- 1.2 Who might require this dataset 10
- 1.3 What the dataset shows 10

2 Case study: A national assessment of landslide hazard from outside party slopes to the rail network of Great Britain 11
- 2.1 The challenge 11
- 2.2 The solution 11
- 2.3 The outcomes and value 11

3 Methodology 12
- 3.1 Availability of debris material 12
- 3.2 Hydrological conditions (permeability) 12
- 3.3 Slope characteristics 13
- 3.4 Model integration 13

4 Technical Information 14
- 4.1 Scale 14
- 4.2 Coverage 14
- 4.3 Attribute description 15
- 4.4 Data format 16
- 4.5 Data history 16
- 4.6 Displaying the data 17

5 Limitations 17
- 5.1 Data content 17
- 5.2 Scale 18
- 5.3 Accuracy and uncertainty 18
- 5.4 Artefacts 19
- 5.5 Disclaimer 20

6 Frequently asked questions 21

Glossary 23

References 26

FIGURES

Figure 1 Example of BGS Debris Flow Susceptibility Model for Great Britain (v6.1) at 1:50 000 in the Cairngorm region of Scotland (viewed at 30% transparency). Contains Ordnance Survey data © Crown Copyright and database rights 2022, Licence No. 100021290.......... 5

Figure 2 Examples of debris flows in Lairig Grhu, Cairngorms, Scotland. Image courtesy of Google Earth Version 9.159.0.0 (May 11, 2022). Lairig Ghu, Scotland. 57⁰05'46"N, 3⁰42'04"W, Eye alt 871m. CNES/Airbus 2019. http://earth.google.com [May 11, 2022]........ 6

Figure 3 (a) Hillslope and (b) channelised debris flow. Taken from Nettleton *et al*. (2005) © Crown Copyright 2005 7

Figure 4 Debris flows in Lairig Grhu, Cairngorms, Scotland showing upslope source area, narrow track. levée features and deposition zone on lower slopes. Image courtesy of Google Earth Version 9.159.0.0 (May 23, 2022). Lairig Ghu, Scotland. 57⁰06'23"N, 3⁰42'39"W, Eye alt 691m. CNES/Airbus, Landsat/Copernicus, Data SIO, NOAA 2019. http://earth.google.com [May 23, 2022] 7

Figure 5 A85 Debris Flow at Glen Ogle. 57 people were trapped in their cars. BGS © UKRI 2004. P641004. 9

Figure 6 Debris flow deposit blocking the A83 Rest and Be Thankful, August 2012. BGS © UKRI 2012 P785430. 9

Figure 7 Recent debris flows on the A83 Rest and Be Thankful Pass BGS © UKRI 2012 P785411. 10

Figure 8 Flow diagram showing the methodological approach used to develop the BGS Debris Flow Susceptibility Model for GB (v6.1).. 13

Figure 9 Extent of coverage of the BGS Debris Flow Susceptibility Model for GB (v6.1).......... 14

Figure 10 Example of BGS Debris Flow Susceptibility Model for Great Britain (v6.1) at 1:50 000 near Quorn, Leicestershire (viewed at 15% transparency) showing examples of anthropogenic slopes (quarries, roads and railways) with high debris flow model values. Contains Ordnance Survey data © Crown Copyright and database rights 2022, Licence No. 100021290.. 20

TABLES

Table 1 Attributes of the BGS Debris Flow Susceptibility Model for GB (v6.1)......................... 15

Table 2 Legend descriptions for the BGS Debris Flow Susceptibility Model for GB (v6.1)........ 15

Table 3 Previous version of the BGS Debris Flow Susceptibility Model for GB 16

Table 4 Current version of the BGS Debris Flow Susceptibility Model for GB 17

Table 5 Colour table to BGS Debris Flow Susceptibility Model for GB (v6.1) 17

Summary

A debris flow is when there is a “rapid downslope flow of poorly-sorted debris mixed with water” (Ballantyne, 2004). The BGS Debris Flow Susceptibility Model for Great Britain (v6.1) is a 1:50 000 scale raster dataset of Great Britain providing 50 m ground resolution information on the susceptibility/ spatial likelihood, at a given location, to initiate a debris flow. It is based on a combination of geological, hydrogeological and geomorphological data inputs and is primarily concerned with potential ground stability related to natural (rather than anthropogenic) geological and geomorphological conditions.

The dataset is designed for those interested specifically in debris flow susceptibility at a regional or national planning scale such as those involved in construction or maintenance of infrastructure networks (road or rail or utilities), or other asset managers such as for property (including developers and home owners), loss adjusters, surveyors or local government.

The dataset builds on research BGS has conducted over the past 15 years investigating debris flows. The model underpinning the dataset was designed to identify potential source areas for debris flows rather than identify the locations where material may be deposited (i.e. the track and debris deposit). It focuses on the natural geology and geomorphological controls that are likely to influence the formation of debris flows. It therefore, does not consider the influence of anthropogenic slopes (such as embankments, cuttings, quarry slopes) beyond their identification in the underpinning slope model input, nor does it consider land use or land cover factors.

This user guide provides the information required to enable the reader to understand and use this BGS data product.

1 Introduction

The BGS Debris Flow Susceptibility Model for Great Britain (BGS DFSM-GB) v6.1 is a 1:50 000 scale raster dataset of Great Britain providing 50 m ground resolution information of where, given the underpinning data, there is potential for a debris flow to be initiated given the ground conditions present.

The BGS DFSM-GB, illustrated in Figure 1, represents an interpretation of where debris flows could occur given particular natural (rather than anthropogenic) geological, hydrogeological and geomorphological properties determined by geological experts and identified through the underpinning data. It was designed to identify potential source areas for debris flows rather than identify the locations where material may be deposited following a long-run-out failure i.e. the flow and debris deposits. It, therefore, does not provide information about the impacts debris flows may have downslope. Other types of landslides may also be present in areas highlighted as susceptible to debris flow such as rockfalls and slides.

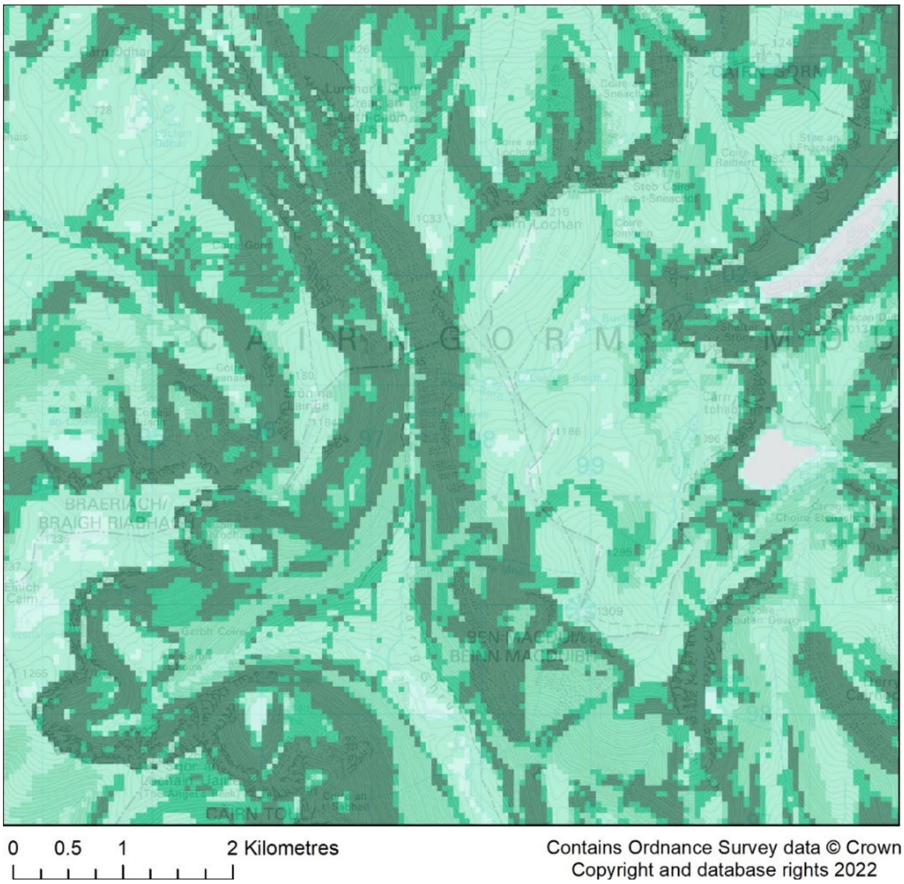

Figure 1 Example of BGS Debris Flow Susceptibility Model for Great Britain (v6.1) at 1:50 000 in the Cairngorm region of Scotland (viewed at 30% transparency). Contains Ordnance Survey data © Crown Copyright and database rights 2022, Licence No. 100021290.

The BGS DFSM-GB examines the conditions that leave an area predisposed to a debris flow occurring; it does not consider the temporal frequency or magnitude of a potential event nor the vulnerability, or exposure of people or assets nor does it consider the influence of land use or land cover factors on debris flow susceptibility. It is designed for those interested specifically in debris flow susceptibility at a regional or national planning scale such as those involved in construction or maintenance of infrastructure networks (road or rail or utilities), or other asset managers such as for property (including developers and home owners), loss adjusters, surveyors or local government.

1.1 BACKGROUND TO THE DATASET

Society's understanding of the effect that ground conditions have on asset safety and infrastructure resilience and value is growing. Local councils are under increasing pressure from central government to provide environmental information. Information about geological hazards is needed, in particular, the identification of areas with a potential for ground movement.

In response to this, the BGS initiated a development programme to produce datasets that identified and assessed potential geohazards threatening the human environment in Great Britain: GeoSure. The BGS GeoSure ground stability data consist of six data layers in GIS format that identify areas of potential hazard in Great Britain. One of these six layers is concerned with landslides and best simulates shallow translational and rotational landslide types (for information about landslide types see Hungr *et al*., 2014; Cruden and Varnes 1996). In order to incorporate another damaging type of landslide common in upland Britain (debris flows), the BGS DFSM-GB dataset has been developed.

Interest in expanding the BGS GeoSure capability to include debris flows primarily arose following a series of debris flows that affected main roads in Scotland in 2004. These events led to the commissioning of the 'Scottish Road Network Landslides Study' by the Scottish Executive (Winter *et al*., 2008). This review assessed the slopes adjacent to the trunk road network and identified areas that had the greatest potential for similar debris flow events in the future. The BGS DFSM-GB described here builds on research BGS has conducted over the past 15 years investigating debris flows. Data sources have been updated and the model has been upscaled to extend coverage to the whole of Great Britain.

1.1.1 What are debris flows?

Ballantyne (2004) describes a debris flow as "the rapid downslope flow of poorly-sorted debris mixed with water". They are a widespread phenomenon in mountainous terrain and in Great Britain are most commonly found in upland Scotland but also in parts of Wales and the Lake District (e.g. Figure 2). Debris flows occur when particular slope characteristics (such as regolith, gradient, drainage, sources of water, or the actions of people) combine to make the slope unstable. Debris flows are potentially very destructive and, due to the speed at which they take place, can rapidly block infrastructure routes, damage assets and pose a risk to life.

Figure 2 Examples of debris flows in Lairig Grhu, Cairngorms, Scotland. Image courtesy of Google Earth Version 9.159.0.0 (May 11, 2022). Lairig Ghu, Scotland. 57⁰05'46"N, 3⁰42'04"W, Eye alt 871m. CNES/Airbus 2019. http://earth.google.com [May 11, 2022]

In Great Britain, there are two types of debris flow (Cruden and Varnes, 1996; Ballantyne, 2004; Nettleton *et al*., 2005);

- *Hill Slope* or *Open-Slope Debris Flows* form their own path down valley slopes as tracks or sheets and deposit material on the lower slopes where the gradient shallows.
- *Valley-confined* or *Channelised Debris Flows* originate in bedrock gullies and are channelled for at least part of their length along the gully floor. The flows have the consistence equivalent to that of wet concrete and can be fronted by a boulder concentration or 'head'.

These are illustrated in Figure 3. The two categories are transitional; many valley-confined flows debouch on to open ground in their lower reaches, and hillslope flows often follow shallow gullies cut in valley-side drift, talus or regolith.

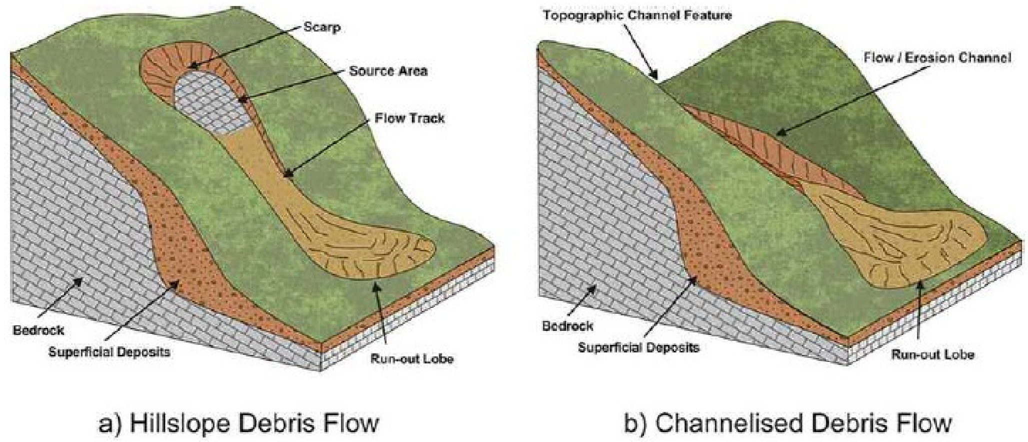

Figure 3 (a) Hillslope and (b) channelised debris flow. Taken from Nettleton *et al*. (2005) © Crown Copyright 2005

Figure 4 Debris flows in Lairig Grhu, Cairngorms, Scotland showing upslope source area, narrow track. levée features and deposition zone on lower slopes. Image courtesy of Google Earth Version 9.159.0.0 (May 23, 2022). Lairig Ghu, Scotland. 57^{0}06'23"N, 3^{0}42'39"W, Eye alt 691m. CNES/Airbus, Landsat/Copernicus, Data SIO, NOAA 2019. http://earth.google.com [May 23, 2022]

Debris flow initiation can occur through a number of mechanisms including as a result of an initial landslide, mobilisation of material in channels as a result of runoff or overland flow, rapid snow melt or run off onto unconsolidated sediments (Hungr *et al*., 2014, Hürlimann *et al*, 2019). Most debris flows in Great Britain occur following a period of high magnitude (prolonged duration and/or high intensity) precipitation events.

Debris flows have an elongate form comprising of a source area, a narrow track and a depositional zone producing a fan or lobate structure on lower angled ground. (e.g. Figure 4). (Ballantyne, 2004). Characteristic features used to distinguish debris flow material from other sediment on a fan include high slope angle of the fan, very large individual particles, coarse levées and boulder trains, signs of impact loading on obstacles, U-shaped eroded channels and steep, debris-loaded channels upstream (Hungr *et al*., 2014).

The BGS DFSM-GB dataset focusses on the identification of the potential source areas. Other types of landslides, including rock falls and slides, may be highlighted by the model as susceptible to debris-flow.

1.1.2 Debris flow impacts

Debris flows are potentially very destructive as they can cause significant erosion of the substrates over which they flow, thereby increasing their sediment charge and further increasing their erosive capabilities (Nettleton *et al*., 2005). The Scottish road and rail networks in particular have been affected by debris flows. Disruptive events have included:

- the A85 road at Glen Ogle where 57 people were stranded on the roadway between two debris flows in 2004 (Figure 5 and British Geological Survey 2004);
- the western slopes of Stob Coire Sgriodain by Loch Treig, in the Scottish Highlands where a train was derailed in 2012 (British Geological Survey 2012); and
- the A83 Rest and Be Thankful Pass, the most widely reported locality for debris flows, much more than any other part of the trunk road network in Scotland (Figure 6 and Figure 7; Winter *et al*., 2013). The Rest and Be Thankful is the main route between Arrochar and Inverary through mountainous terrain. When this road is closed, a 55-mile detour and associated high economic consequences are regularly reported in the media. Wig-wag warning systems (Winter *et al*., 2013) were installed in 2011 and ten bespoke debris flow barriers in 2014 (Maccaferi, 2014).
- debris flows occurred at Lochailort on the 11th August, 2016. An estimated 100 t of debris were deposited at the slope foot covering a 70-m-long section of the Fort William to Mallaig railway line and part of the A830 (Palamakumbura *et al*., 2021)
- a debris flow derailed a passenger train near Glenfinnan on the 22nd of January 2018. A combination of snowmelt, ground thaw and rainfall (following an unusually wet January) triggered the event which occurred above the railway line and involved approx. 1000 tonnes of material (RAIB, 2018).

Figure 5 A85 Debris Flow at Glen Ogle. 57 people were trapped in their cars. BGS © UKRI 2004. P641004.

Figure 6 Debris flow deposit blocking the A83 Rest and Be Thankful, August 2012. BGS © UKRI 2012 P785430.

Figure 7 Recent debris flows on the A83 Rest and Be Thankful Pass BGS © UKRI 2012 P785411.

1.2 WHO MIGHT REQUIRE THIS DATASET

Debris flows may lead to financial loss for anyone involved in the ownership or management of infrastructure assets (e.g. road, rail), utilities or property, including developers, householders, loss adjusters, surveyors or local government. Costs could include increased insurance premiums, depressed house prices and, in some cases, engineering works to stabilise land or property. Armed with knowledge about potential debris flows, preventative steps can be put in place to alleviate the impact of the hazard to people and assets. The cost of such prevention may be low, and is often many times lower than the repair bill following ground movement.

The BGS DFSM-GB is designed for those interested in debris flow susceptibility at a regional or national planning scale rather than at a site-specific scale. It can be used as an initial phase desk-study analysis tool, but does not replace detailed site investigations.

1.3 WHAT THE DATASET SHOWS

This addition to the BGS GeoSure ground stability data consists of a single raster data layer for use in a Geographical Information System (GIS) that identifies potential source areas of debris flow hazard. It is a debris flow susceptibility map for Great Britain. These data have been produced by engineering geologists and data scientists at the BGS and is presented as a digital raster spatial dataset at 1:50 000 scale providing 50 m ground resolution information.

The BGS DFSM-GB was designed to identify potential source areas for debris flows rather than identify the locations where material may be deposited (i.e. the track and debris deposit). It focuses on the natural geology and geomorphological controls that are likely to influence the formation of debris flows. It therefore, does not consider the influence of anthropogenic slopes (such as embankments, cuttings, quarry slopes) beyond their identification in the underpinning slope model input, nor does it consider land use or land cover factors.

2 Case study: A national assessment of landslide hazard from outside party slopes to the rail network of Great Britain

2.1 THE CHALLENGE

During the last decade a number of landslides have occurred in Great Britain which have caused disruption to rail travel, train derailments or damage to railway infrastructure and consequently received significant media attention. Examples of high-profile cases are documented in the UK Governments Rail Accident Investigation Branch (RAIB) annual reports and event specific reports. Debris flow events that have recently impacted the railway network include the 2014 debris flow and train derailment at Loch Treig (Stob Coire), disruption to the line at Lochailort (2016) and a train derailment at Loch Eilt (January 2018) in the Scottish Highlands (Freeborough *et al*. 2019). These events involved material from outside of the Network Rail (NR) boundary falling onto the tracks.

Network Rail is responsible for the monitoring and maintenance of all earthwork assets within its property boundary. However, potentially hazardous slopes that occur outside of the Network Rail property boundary, but which are owned or managed by an outside party, known as Outside Party Slopes (OPS), and which could affect the rail network have been identified as a key priority for strategic Network Rail operating plans under the standard "Management of Earthworks Manual NR/L2/CIV/086".

The BGS were contracted to compile a high-level landslide susceptibility model, confined to landslide hazards originating from OPS adjacent to the national rail network. Outputs from the BGS DFSM-GB (v6.0) were included in this hazard assessment.

2.2 THE SOLUTION

The study (Freeborough at al., 2019) adopted a structured buffer analysis of each of Network Rail's Earthwork Inspection 5 chain (c100 m) sections of the entire railway network. The model was produced by combining the BGS GeoSure land instability model with national models for debris flow, earth flow and rock fall. It also included landslide event data from the BGS National Landslide Database, landslide polygons from geological maps ('BGS Geology 50k' formerly known as DiGMap50) and Network Rail's own records of failures attributed to OPSs. A buffer of influence was created by Network Rail to focus the potential OPS zone for the national output.

Each Earthwork Inspection chain was categorised using a 'Classification of Hazards on Outside Party Slopes' (CHOPS) A-E hazard rating; where E indicates a significant potential for hazard as indicated by the underlying datasets. The outputs are combined in a series of matrices with NR criticality banding assessments.

As highlighted by the examples of train derailments above, debris flows are a serious issue for asset owners like Network Rail, especially in upland areas of Scotland. The BGS DFSM-GB version 6.0 was used in this case study to supplement the existing GeoSure slope stability layer and provide debris flow specific susceptibility assessments along the rail corridor.

2.3 THE OUTCOMES AND VALUE

This project provided Network Rail with a high-level initial assessment of the entire network, based on Geographic Information System (GIS) data analysis techniques, Network Rail data and historical landslide records (landslide inventory). Around 6% of the network as a whole was modelled to be susceptibility to debris flows. The spatial distribution of high BGS DFSM-GB ratings in proximity to the network allowed senior management and individual Route Asset Managers (RAMs) to more fully understand the nature and potential extent of this particular hazard.

2.3.1 Network Rail Testimonial

"The work done by BGS on outside party slopes has allowed Network Rail to understand which parts of the network might be at risk from adjacent natural slopes. Outside party slope problems have caused a number of derailments in recent years, and this study is an essential first stage to allow us to manage this issue. A key part of the success of this work was being able to combine Network Rail's understanding of the railway network with the expertise of the BGS in using their national datasets and knowledge of UK geology to model the susceptibility of natural slopes". Neil Esslemont, Senior Engineer (Buildings & Civils), Network Rail. February 2022.

3 Methodology

The BGS DFSM-GB (v6.1) has been created by deriving three input layers which reflect the 1) availability of debris material; 2) hydrogeological conditions (permeability/infiltration potential); and 3) slope characteristics at the respective locations. These three input variables are described in turn in the following sub sections of this report.

Land use was not considered as a variable in this methodology. Vegetation may have a beneficial effect on slope stability e.g. intercepting rainfall, removing soil moisture and reinforcement of the ground through root networks, but the amount of stabilisation will vary with the type of vegetation and the season. Experience working on a number of projects with the Forestry Commission (a non-ministerial government department responsible for forestry in England, Scotland and Wales) highlighted the fact that even though an area may be designated as woodland it is not always completely planted and there can be forest roads and firebreaks that could increase the potential for debris flows. Given this experience and the knowledge that land use can change with time, the BGS DFSM-GB (v6.1) focusses on the geological factors that contribute to debris flows. It is recommended that, where it exists, local knowledge and detailed land use data is used to supplement the data.

3.1 AVAILABILITY OF DEBRIS MATERIAL

The 'availability of debris material' input layer was primarily derived using the BGS Soil Parent Material Model (SPMM) (v6). Using a ten-point scale, BGS Experts classified geological materials according to texture and the characteristics of any weathering products (regolith) that may be mantling slopes and that could become involved in a debris flow.

Ballantyne (2004) highlighted that debris flows are scarce in areas of extensive glacial scouring such as the Outer Hebrides, Knoydart, Morven and Argyll. These areas are largely devoid of superficial deposits and having experienced severe, widespread glacial erosion resulting in very thin or non-existent soil with minimal occurrence of deeply weathered bedrock. Consequently, it can be expected that there is less material available for debris flows to occur in such areas.

Further refinement of the 'availability of debris material' input layer was required to consider areas where material may have been removed from the slopes and would therefore not be available to be mobilised. This was achieved by creating an 'Ice-scoured domain' polygon using BGS Quaternary domain and landslide domain knowledge and applying it within the model to reduce the 'availability of material' classification scores at such locations.

3.2 HYDROLOGICAL CONDITIONS (PERMEABILITY)

Since debris flows are usually triggered by intense precipitation events, the hydrological conditions of a site are important when determining susceptibility to these types of failures.

A dataset, BGS Geological Controls on Infiltration v8 (BGS GCI), was specifically created by the project team as an input to the BGS DFSM-GB (v6.1). The GCI methodology for the BGS DFSM-GB was developed in conjunction with BGS hydrogeology experts and considered two principle criteria to determine whether a material was less or more susceptible to a debris flow due to its hydrological characteristics:

- *The ability of water, as rainfall or overland flow to infiltrate a potentially mobile deposit (permeability of the deposit)*
- *The ability of water to remain within the deposit to an extent where pore water pressures can build to a level where the shear strength is sufficiently reduced to initiate failure (permeability of the underlying material)*

The GCI input layer has developed using the following data:

1. BGS Superficial Permeability (v8)
2. BGS Bedrock Permeability (v8)
3. BGS Superficial Thickness Model (v5)

3.3 SLOPE CHARACTERISTICS

A key control on debris flow initiation is slope angle. A smoothed slope map was created from a 5 m DTM licenced from Bluesky International Ltd. This slope map was used to classifying slope angles into ranges (based on published literature on debris flow initiation) and to identify the presence of channels on critical slopes. Channels were identified by identifying 'hollow' landforms using the smoothed approach of Jasiewicz and Stepinski (2013).

3.4 MODEL INTEGRATION

The three input layers the 1) availability of debris material; 2) hydrogeological conditions; and 3) slope characteristics were then integrated to produce the BGS DFSM-GB. Figure 8 shows a conceptual diagram of how the BGS DFSM-GB (v6.1) was developed using these three primary input layers and the ice scoured montane domain.

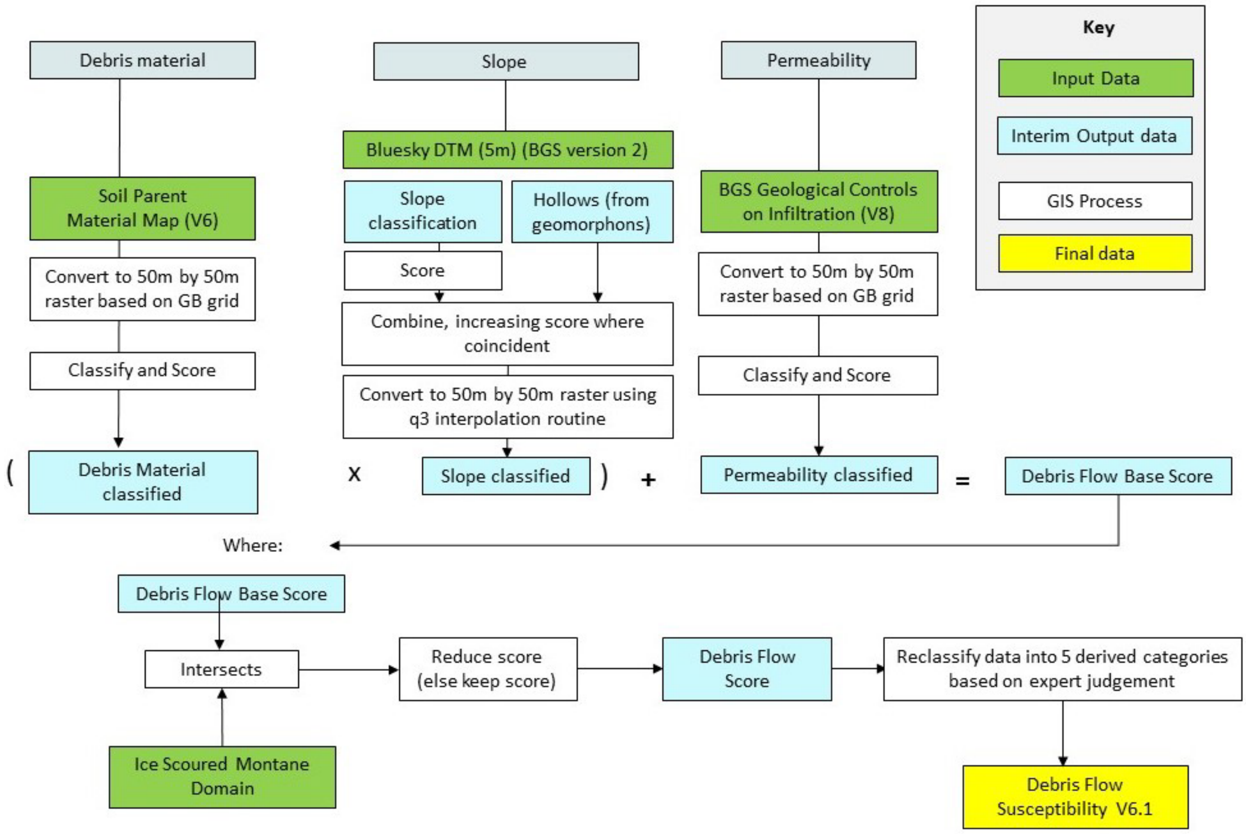

Figure 8 Flow diagram showing the methodological approach used to develop the BGS Debris Flow Susceptibility Model for GB (v6.1)

4 Technical Information

4.1 SCALE

The BGS DFSM-GB (v6.1) dataset is produced for use at 1:50 000 scale providing 50 m ground resolution. The dataset is not suitable for use at larger (i.e. more detailed) scales, for example 1:50 000 scale data should not normally be enlarged and used at 1:10 000 scale.

4.2 COVERAGE

The BGS DFSM-GB (v6.1) covers Great Britain (Figure 9). This does not include the Isle of Man, the Channel Islands or Northern Ireland.

Figure 9 Extent of coverage of the BGS Debris Flow Susceptibility Model for GB (v6.1).

The dataset is not a complete mosaic. There are several areas within mainland Great Britain which have values of 'No Data'. These generally occur where there are inland bodies of water such as lakes. Where the underlying geological mapping within the BGS SPMM (v6) data shows these areas to be 'NA', it was not possible to assign a lithology score and the cell is therefore recorded as 'No Data'. In some areas, which are coincident with water bodies, the geological map has attributed the underlying surface geology with a lithology. In such cases, a score was possible and as such, the cell was assigned with a score rather than a 'No Data' value.

4.3 ATTRIBUTE DESCRIPTION

Table 1 shows the attributes of the BGS DFSM-GB Dataset.

Table 1 Attributes of the BGS Debris Flow Susceptibility Model for GB (v6.1)

Field name	Field description
VALUE	An automatically generated number (1-5) to represent each discrete category in the dataset.
COUNT	The number of cells within the associated [Value] field.
LEGEND	Classification of the susceptibility to debris flow on a scale of A -E
SHORT_DESC	Description of the debris flow susceptibility classification
VERSION	Dataset name and version number (DFSM_GB_V6.1)

The BGS DFSM-GB (v6.1) provides a susceptibility rating as an A-E classification in its 'Legend' field, representing increasing likelihood to debris flow susceptibility. Descriptions of what these values represent are shown in (Table 2).

Table 2 Legend descriptions for the BGS Debris Flow Susceptibility Model for GB (v6.1)

Legend	SHORT_DESC	Longer description/ Interpretation (not included in spatial layer)
A	The naturally occurring geological and geomorphological conditions suggest that debris flows are unlikely to occur.	The naturally occurring geological and geomorphological conditions observed in the data suggest that debris flows are unlikely to occur at these sites. This is due to a lack of available slope material for flow, high drainage rates or low slope angle.
B	The naturally occurring geological and geomorphological conditions suggest that debris flows are not very likely to occur.	The naturally occurring geological and geomorphological conditions observed in the data suggest that debris flows are not very likely to occur or have occurred at these sites. This is either due to a lack of available slope material for flow, sufficient drainage rates or low slope angles.
C	The naturally occurring geological and geomorphological conditions suggest that debris flows may be present or anticipated.	The naturally occurring geological and geomorphological conditions suggest that debris flows may be present, occurred in the past or anticipated at these sites. The combinations of increasing slope angle, poor drainage conditions and the presence of available slope material for flow may increase the potential for failures to occur.
D	The naturally occurring geological and geomorphological conditions suggest that debris flows are likely to be present.	The naturally occurring geological and geomorphological conditions observed in the data suggest that debris flows are likely to be present, or have occurred in the past, at these sites. The combinations of steep slopes, poor drainage conditions and an increased presence of available slope material for flow may increase the potential for failures to occur.
E	The naturally occurring geological and geomorphological conditions suggest that debris flows are highly likely to be present.	The naturally occurring geological and geomorphological conditions observed in the data suggest that debris flows are highly likely to be present, or have occurred in the past, at these sites. The heightened combinations of steep slopes, poor drainage conditions and the presence of available slope material for flow increases the potential for failures to occur.

4.4 DATA FORMAT

The BGS DFSM-GB (v6.1) dataset is available as a raster GIS dataset with attribute values relating to debris flow susceptibility. It has been created as an ESRI GRID raster file and in ASCII format. Other formats on request, subject to the limitations and availability of translational software.

4.5 DATA HISTORY

4.5.1 Context

BGS GeoSure is a set of six national ground-stability layers developed in vector GIS format at 1:50 000 scale. The six layers include Compressible Ground, Collapsible Ground, Landslides, Running Sands, Soluble Rocks and Shrink–Swell.

Whilst the BGS GeoSure dataset includes a landslides slope instability layer (Dashwood *et al.* 2014), interest in expanding the BGS GeoSure capability to specifically include debris flows primarily arose following a series of debris flows in 2004 that affected main roads in Scotland which led to the Scottish Road Network Landslides Study to be commissioned by the Scottish Executive (Winter *et al*., 2008). Work conducted by Harrison *et al*. (2006) fed into this study. Building upon this initial research by Harrison *et al.* (2006) for parts of Scotland and other research, the BGS DFSM-GB was created in 2017 to provide a regional scale overview of debris flow susceptibility for all of Great Britain.

4.5.2 Previous versions of the BGS DFSM-GB

The BGS DFSM-GB v6.0[1] was released as an evaluation beta dataset in 2017 (Table 3). This provided an additional dimension to the GeoSure Landslides surface layer for users specifically interested in debris flow potential.

Table 3 Previous version of the BGS Debris Flow Susceptibility Model for GB

Name of dataset	Dataset Reference, including DOI
GeoSure Extra: Debris Flow Susceptibility Model for Great Britain (version 6.0).	British Geological Survey (BGS). 2017. GeoSure Extra: Debris Flow Susceptibility Model for Great Britain (version 6.0). Electronic dataset. (British Geological Survey.) DOI: https://doi.org/10.5285/6f46c720-cab3-4c2e-8dad-8bd2f8f1b4ae

The slope input data used in the BGS DFSM-GB (v6.0) was developed using a 50 m derived Digital Terrain Model (DTM) built from a DSM and licensed from NEXTMap™. Given the age and resolution of this DTM, the DFSM-GB product remained in evaluation state (v6.0) until BGS was able to acquire and process a more up-to-date DTM. The BGS DFSM-GB (v6.1) has been developed using a more recently acquired DTM licensed from Bluesky International ltd.

4.5.3 Current version of the BGS DFSM-GB

The latest version of the BGS DFSM-GB is referenced in Table 4. Modifications include an update of the DTM (Licensed from Bluesky International ltd.). The updated DTM is a 5 m resolution with tree cover removed. It is a temporal composite consisting of data collected over the time period 2003-2020 and was compiled using both airborne lidar and aerial photography. A 5 m slope derivative product was developed from this 5 m resolution DTM. The methodology to derive the slope input layer (including identification of channels) in the BGS DFSM-GB was reviewed and updated in light of the updated DTM and slope derivative.

[1] Version 6 refers to the version of BGS Geology 50k used to create the bedrock and superficial permeability datasets used in its creation. This is to be consistent with the way that version numbers have been allocated to other BGS data products derived from BGS Geology 50k

Table 4 Current version of the BGS Debris Flow Susceptibility Model for GB

Name of dataset	Dataset Reference, including DOI
GeoSure Extra: Debris Flow Susceptibility Model for Great Britain (version 6.1).	British Geological Survey (BGS). 2022. GeoSure Extra: BGS Debris Flow Susceptibility Model version 6.1. British Geological Survey. (Dataset). https://doi.org/10.5285/88f7591f-8cbe-4ead-9f0a-85ac25d96d93

The remaining components of the methodology are consistent with v6.0 except that it includes updated data inputs where they existed (e.g. The BGS Geological Controls on Infiltration GB has been updated to version 8 as it has been derived from data which uses BGS Geology 50k v8). Finally, the description text associated with the final A-E classifications have been updated to improve their articulation.

4.6 DISPLAYING THE DATA

The BGS DFSM-GB is displayed through its [Legend] attribute field. This field provides a classification of A to E (Table 2). Table 3 provides information to enable users to display the data in a GIS using its intended colour profile.

Table 5 Colour table to BGS Debris Flow Susceptibility Model for GB (v6.1)

Data Classification	RED	GREEN	BLUE	HEX	LOOKS LIKE
Legend value	This is the equivalent red channel colour	This is the equivalent green channel colour	This is the equivalent blue channel colour	This is the equivalent HEXadecimal value	This cell shows the colour as intended
A	203	245	234	#CBF5EA	
B	166	237	211	#A6EDD3	
C	128	224	184	#80E0B8	
D	48	200	146	#30C892	
E	68	137	112	#448970	

5 Limitations

5.1 DATA CONTENT

The BGS DFSM-GB (v6.1) has been constructed by combining data from the BGS SPMM (v6.1) and the BGS GCI-GB (v8), which uses information from BGS Superficial Permeability (v8) and BGS Bedrock Permeability (v8). These BGS data products are based on our national geological survey information and are a synthesis of several national and regional databases held by BGS, primarily DiGMapGB-50 v6.20 (now renamed BGS Geology 50k).

The BGS Geology 50k dataset is a compilation of digital tiles derived from previously published and unpublished maps and archive information. The mapping, description and classification of rocks are based upon the interpretations and evidence available at the time of survey, or time of re-evaluation for modifications/correction. The BGS DFSM-GB is based on, and limited to, an interpretation of the records in the possession of the BGS at the time the dataset was created.

The BGS DFSM-GB (v6.1) represents an interpretation of where debris flows could occur given particular geological, hydrogeological and geomorphological factors determined by geological experts and identified through the underpinning data. The model is limited to areas where debris flows are initiated. It does not indicate where the material involved in the failure will be deposited.

The model does not include any influence of land cover on the stability of a slope. The stabilising influence of certain types of vegetation is well documented in the literature, however the data available at the national-scale is not updated on a regular basis. Therefore, any changes to vegetation (e.g. a felled forest could have a destabilising effect on the slope) would not be captured until the next release of data which could lead to incorrect assumptions to be made about debris flow potential.

The BGS DFSM-GB (v6.1) is concerned with potential ground instability related to natural geological conditions only. It is not underpinned by a dataset representing anthropogenic slope deposits. However, information about the morphology of slopes modified anthropogenically is included and this is recognised as a limitation of the model (see section 5.4). Application of local knowledge is therefore imperative when using the model to inform decisions.

The level of susceptibility does not mean that a damaging debris flow event is going to happen, or won't happen, but is an indication of how selected causative factors may be present and, due to their combination, conducive to debris flow activity based on the underpinning data. The dataset does not therefore replace site scale assessments made by a qualified professional.

5.2 SCALE

The BGS DFSM-GB (v6.1) dataset is produced for use at 1:50 000 scale providing 50 m ground resolution. The dataset is not suitable for use at larger (i.e. more detailed) scales, for example 1:50 000 scale data should not normally be enlarged and used at 1:10 000 scale. The dataset is designed for those interested in debris flow susceptibility at a regional or national planning scale rather than at a site-specific scale. **The dataset should not be used in place of detailed site investigation reports.**

5.3 ACCURACY AND UNCERTAINTY

The mapping accuracy of some of the data inputs associated with the BGS DFSM-GB (v6.1) is based on that of the BGS Geology 50k dataset. This is nominally 1 mm which equates to 50 m on the ground at 1:50 000 map scale. This is only a measure of how faithfully the lines are captured. Consequently, this dataset must not be used at scales finer than 1:50 000. The BGS DFSM-GB (v6.1) is a raster product, whereby a single value is given to each 50 m by 50 m cell depending on the data observed within that cell. The raster cell value for the geological and hydrogeological inputs to the model were given the maximum score (conservative approach) observed in the cell, irrespective of the polygon area. This was in an attempt to account for the spatial uncertainty and scale of the underpinning data.

The BGS DFSM-GB v6.1 has been evaluated in a number of areas where we know debris flows to be present and have been observed such as in the upland areas of the Lake District, Snowdonia, Cairngorms, Glen Coe and the Rest and Be Thankful area. Statistical validation of the model using a spatially limited debris flow inventory suggests it performs reasonably well, with areas of mapped debris flow activity corresponding well to areas of high susceptibility highlighted by the model. It is however difficult to evaluate the model in areas where the records of debris-flows are limited or not observed, and the accuracy of the model is therefore less certain in these areas.

5.3.1 Digital Terrain Model

A slope model was derived directly from a Digital Terrain Model (DTM) licensed from Bluesky International Ltd. This is a 5 m resolution DTM where tree cover has been removed, compiled using both airborne lidar and aerial photography. The DTM is a temporal composite consisting of data captured over the time period 2003-2020. The DTM was not prior-smoothed or pre-processed. For the purposes of the flow modelling required for the debris flow product development, the DTM was used to generate surface derivatives pertaining to surface slope and to extract 'hollow' landforms based on the 'geomorphons' approach by Jasiewicz, J., Stepinski, T. (2013).

Terrain derivatives are inherently sensitive to uncertainties in elevation models (e.g. Smith *et al.,* 2019) and, where derivatives are to act as input as part of larger numerical modelling sequences, any uncertainties can easily be propagated which can distort end results. The licensed Bluesky International Ltd. DTM was filtered prior to the calculation of terrain derivatives using a feature preserving smoothing algorithm to minimise the impact of subtle shifts in elevation within the DTM related to collection line artefacts and the underlying methods of multi-temporal data compilation. This enables the removal of subtle noise whilst ensuring that the dominant signal inherent in the elevation model is disturbed as little as possible. The filtered DTM was then used to calculated slopes and create a geomorphons layer following the approach of Jasiewicz and Stepinski (2013). The calculation of geomorphons is an inherently scale specific process whereby different settings could result in different outputs due to the interaction between search radius size and elevation data distribution. For this reason, the same geomorphon input parameters were maintained for nationwide application and all results relating to this surface are therefore comparable.

5.3.2 Slope classification

Each 5 m cell was attributed with a score based on the slope value and the presence of a ‘hollow’ from the geomorphons layer. The slope ranges used to derive the input score for the slope component to the debris flow model were based on value ranges identified within relevant literature. Whilst these slope ranges were applied consistency across Great Britain and reflect our current understanding from published literature, it is likely that debris flows may occur at subtly different slope angle ranges in different geological domains in the country. There may be an opportunity for future updates to the BGS DFSM-GB (v6.1) to include landslide domain specific knowledge as new research is undertaken and published.

A slope classification score for each 50 m cell was required as an input into the final national scale model. Each 50 m cell was therefore attributed with the 75th percentile value (q3) of all the 5 m cells (possible range 0-10) within the 50 m cell. This method of generalisation ensured that the range of values from the 5 m cell data were represented within the 50 m cell, remaining cautionary without being too conservative at this smaller scale. Consequently, the highest value observed in a matrix of 5m cells (within the 50m cell) will only be preserved in the final 50m by 50m raster output if this highest value is represented in at least 25% of the 50m by 50m cell coverage. This means that small hollows which exist in isolation, and/or the area or amount of a critical slope angle is too small, these features won’t be captured in the final 1:50,000 scale product.

5.4 ARTEFACTS

The underpinning BGS Geology 50k dataset represents data from different times and origins. This can result in disagreements between older and more recently gathered observations (such as boreholes). Consequently, adjacent geological sheets/tiles (of different survey dates) may not seamlessly fit together spatially, or in terms of lithological description. This can result in some map-sheet ‘edges’ that exhibit contrasting colours/attribution which can propagate into the final values of the BGS DFSM-GB.

The product does occasionally highlight locations that have high debris flow susceptibility scores which are due to the underpinning DTM. These tend to be as a result of anthropogenic slopes (e.g. beside worked quarries, railway cuttings and embankments etc) within certain areas where the natural geological conditions support a high score (see Figure 10 for an example). The model does not account for any mitigating engineering factors that may be in place at these or any other locations. Application of local knowledge is therefore imperative when using the model to inform decisions.

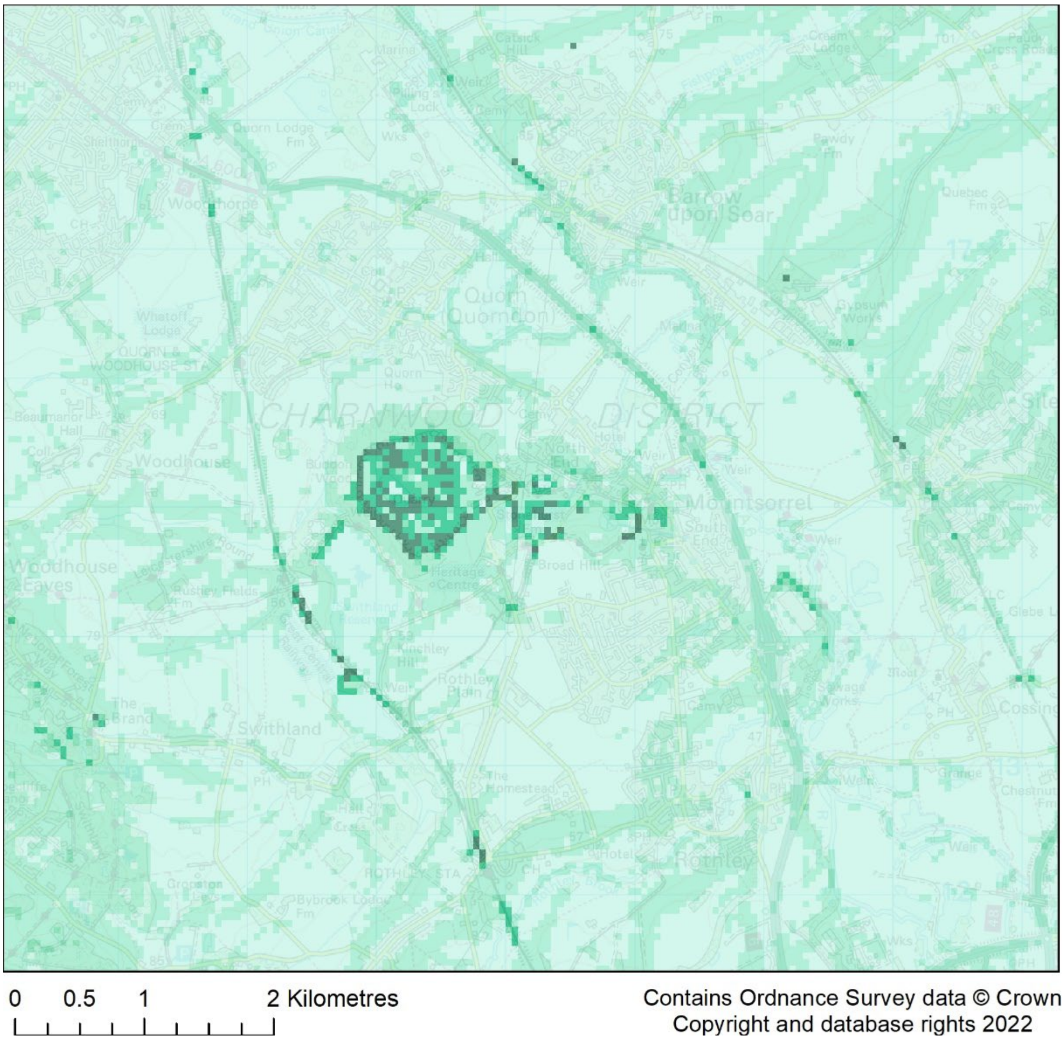

Figure 10 Example of BGS Debris Flow Susceptibility Model for Great Britain (v6.1) at 1:50 000 near Quorn, Leicestershire (viewed at 15% transparency) showing examples of anthropogenic slopes (quarries, roads and railways) with high debris flow model values. Contains Ordnance Survey data © Crown Copyright and database rights 2022, Licence No. 100021290.

5.5 DISCLAIMER

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Components of the Debris Flow product are developed using data obtained from 3rd parties. Whilst BGS strives to make its products as accurate as possible, we can offer no warranty about fitness-for-purpose or accuracy of information. Furthermore, the information provided is the result of modelled output and thus provided as 'best available', scientifically modelled data only.

6 Frequently asked questions

These questions and answers have been provided to address any potential issues relating to how the product can be used or how it can be interpreted. If you have any additional questions, please contact digitaldata@bgs.ac.uk

Q: What does the BGS DFSM-GB dataset show?
A: The BGS DFSM-GB is a 1:50 000 scale raster dataset of Great Britain providing 50 m ground resolution information on the susceptibility/spatial likelihood, at a given location, to initiate a debris flow. The dataset provides a susceptibility rating as an A-E classification in its 'Legend' field, representing increasing debris flow susceptibility. This rating is based on a combination of geological, hydrogeological and topographic data inputs and is primarily concerned with potential ground stability related to natural (rather than anthropogenic) geological conditions and slopes.

Q: Who should use the dataset?

A: The dataset is designed for those interested specifically in debris flow (a specific type of landslide) susceptibility at a regional or national planning scale such as those involved in construction or maintenance of infrastructure networks (road or rail or utilities), or other asset managers such as for property (including developers and home owners), loss adjusters, surveyors or local government.

Q: What areas does the BGS DFSM-GB dataset cover?
A: This dataset covers Great Britain. This does not include the Isle of Man, the Channel Islands or Northern Ireland.

Q: In what data formats can the BGS DFSM-GB Dataset be provided?
A: The BGS DFSM-GB (v6.1) dataset is available as a raster GIS dataset with attribute values relating to debris flow susceptibility. It has been created as an ESRI GRID raster file and in ASCII format. Other formats may be available but may incur additional processing costs. Please email iprdigital@bgs.ac.uk to request further information.

Q: At what map scale is the BGS Debris Flow Susceptibility Model Great Britain dataset provided?
A: The BGS DFSM-GB (v6.1) dataset is produced for use at 1:50 000 scale providing 50 m ground resolution. The dataset is not suitable for use at larger (i.e. more detailed) scales, for example 1:50 000 scale data should not normally be enlarged and used at 1:10 000 scale.

Q: How accurate is the BGS Debris Flow Susceptibility Model Great Britain dataset?
A: The level of susceptibility indicated by the BGS DFSM-GB reflects the presence of selected causative factors which may, due to their presence and combination, lead to increased likelihood of debris flow initiation. An indication of natural ground susceptibility does not necessarily mean that a slope will be affected by future debris flow initiation. Such an assessment can only be made by inspection of the area by a qualified professional.

The BGS DFSM-GB (v6.1) is concerned with potential ground stability related to natural geological conditions only. It therefore, does not consider the influence of anthropogenic slopes (such as embankments, cuttings, quarry slopes) and is not underpinned by a dataset representing anthropogenic slope deposits. Information about the morphology of slopes modified anthropogenically is therefore included in the dataset and recognised as a limitation of the model. Application of local knowledge is therefore imperative when using the model to inform decisions.

The mapping accuracy of some of the data inputs associated with the BGS DFSM-GB (v6.1) is based on that of the BGS Geology 50k dataset. This is nominally 1 mm which equates to 50 m on the ground at 1:50 000 map scale. This is only a measure of how faithfully the lines are captured and is based on geological interpretations rather than definitive fact. Consequently, this dataset must not be used at scales finer than 1:50 000.

Q: How often will the BGS Debris Flow Susceptibility Model Great Britain Dataset be updated?

A: This dataset is not routinely updated however the dataset is revised on an ad hoc basis, when there are significant changes in its source data, and/ or new research outputs.

Q: Can I use the BGS Debris Flow Susceptibility Model Great Britain as part of a commercial application?
A: This dataset is licenced from BGS, please refer to the terms of your licence or contact iprdigital@bgs.ac.uk for further information.

Glossary

Term	Explanation
ASCII grid	American Standard Code for Information Interchange (ASCII) data format for the storage of raster data. The ASCII raster format can be used to store cell based or raster information. The basic structure of an ASCII grid has the header information at the beginning of the file followed by the cell value data.
Attribute	Named property of an entity. Descriptive information about features or elements of a database. For a database feature like census tract, attributes might include many demographic facts including total population, average income, and age. In statistical parlance, an attribute is a variable, whereas the database feature represents an observation of the variable.
Bedrock	The main mass of rocks forming the earth, laid down prior to 2.588 million years ago. Present everywhere, whether exposed at the surface in rocky outcrops or concealed beneath superficial deposits, artificial ground or water. Formerly called solid.
Debris flow	“The term debris-flow refers to the rapid downslope flow of poorly-sorted debris mixed with water” (Ballantyne, 2004).
DEM (Digital Elevation Model)	The elevation of the bare-Earth, removing all natural and built features.
DTM (Digital Terrain Model)	An augmented Digital Elevation Model (DEM) that incorporates the elevation of important topographic features on the natural terrain such as rivers and ridges.
ESRI	Environmental Systems Research Institute (ESRI) is an international supplier of geographic information system (GIS) software, web GIS and geodatabase management applications.
Formation	Part of the BGS rock-age ordering hierarchy. A formation is the fundamental rock unit for mapping purposes. Located within a defined hierarchical structure Supergroup>Group>FORMATION>Member>Bed
Geographical Information System	Geographic Information Systems (GIS) provides accurate information, assistance, support, and maintains and creates information to aid in the development of maps and data analysis.
Geohazard	Geological and environmental conditions, involving long and short-term processes which may lead to widespread damage. There are many different types of geohazard with different natural and artificial processes causing them to occur. All have the potential to create problems for development of the human environment and threats to the safety and well-being of people. Geohazards can develop quickly (seconds or minutes) in response to the processes that drive them, or take tens, hundreds, or thousands of years to develop to a point where they pose a danger. They are found in most parts of the world, including marine and fluvial environments.
Geology	The study or science of the earth, its history, and its life as recorded in the rocks; includes the study of geologic features of an area, such as the geometry of rock formations, weathering and erosion, and sedimentation.
Geomorphon	A term coined by Jasiewicz, J., Stepinski, T. (2013) to describe the geomorphological landform elements that can be extracted from a DEM through applying a pattern recognition algorithm.
Geospatial data	Data that has a geographic component to it. This means that the records in a dataset have locational information tied to them such as geographic data in the form of coordinates, address, city, or postcode.

Glacial	Material deposited by glaciers. Glacial deposits are poorly sorted consisting of mostly coarse-grained sediments i.e. sand and gravel; with some finer-grained layers i.e. clay and silt.
Glacial scouring	Erosion of surface material as a result of glacial activity.
Hazard	"A dangerous phenomenon … that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage" (UNDRR, 2009). In the case of this work, refers to a debris flow event.
Hazard rating	Scale or classification used to indicate low to high degree of identified threat.
Ice-scoured Domain	An area that has experienced glacial scouring.
Landslide susceptibility	"The likelihood of a landslide occurring in an area on the basis of local terrain conditions" (Brabb, 1984).
Landslide hazard	The probability of occurrence within a specified period and within a given area of a landslide of given magnitude (Guzzetti *et al*., 1999). Landslide hazard is a function of susceptibility and temporal frequency of landslide triggers.
Landslide risk	The probability of a landslide event occurring multiplied by its consequences (Corominas *et al*., 2014). Risk refers to "the combination of the probability of an event and its negative consequences" (UNDRR, 2009).
Lithological units	A rock identifiable by its general characteristics of appearance colour, texture and composition defined by the distinctive and dominant, easily mapped and recognizable petrographic or lithologic features that characterize it.
Lithology	Rocks maybe defined in terms of their general characteristics of appearance: colour, texture and composition. Some lithologies may require a microscope or chemical analysis for the latter to be fully determined.
Permeability	The term permeability, used in a general sense, refers to the capacity of a rock to transmit water. Such water may move through the rock matrix (intergranular permeability) or through joints, faults, cleavage or other partings (fracture or secondary permeability). A stricter definition of permeability is that it is a measure of the relative ease with which a porous medium can transmit a fluid under a potential gradient. It is the property of the medium only and is independent of the fluid. Commonly, but imprecisely, taken to be synonymous with the term Hydraulic Conductivity which implies the fluid is water.
Quaternary	A geological time period covering the last 2.6 million years.
Quaternary deposits	All unconsolidated material deposited in the last 2.6 million years.
Raster	Raster data can be thought of as being similar to a digital photograph. The entire area of the map is subdivided into a grid of tiny cells, or pixels. A value is stored in each of these cells to represent the nature of whatever is present at the corresponding location on the ground.
Resolution	Resolution expresses the size of the smallest object in a spatial data set that can be described. It refers to the amount of detail that can be discerned. It is also known as granularity.
Risk	The combination of the probability of an event and its negative consequences.
Scale	The relation between the dimensions of features on a map and the geographic objects they represent on the earth, commonly expressed as a fraction or a ratio. A map scale of 1/100,000 or 1:100,000 means that one unit of measure on the map equals 100,000 on the earth.

Scripted	Automating of tasks such as geoprocessing with a GIS environment to build workflows delivering complex data processing and job control. Scripting languages commonly used are Python and Visual Basic.
Source data	Source data is raw data (sometimes-called atomic data) that has not been processed for meaningful use to become Information.
Spatial data	Data describing anything with spatial extent; i.e. size, shape or position. In addition to describing things that are positioned relative to the Earth, spatial data may also describe things using other coordinate systems that are not related to position on the Earth, such as the size, shape and positions of cellular and sub-cellular Spatial Things described using the 2D or 3D Cartesian coordinate system of a specific tissue sample.
Superficial	The youngest geological deposits formed during the most recent period of geological time, the Quaternary. They date from about 2.6 million years ago to the present.
Topographic	The physical features of the Earth. A topographic map's principal purpose is to portray and identify the features of the Earth. These features might include the cultural landscape, but normally refer to the terrain and its relief.

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The British Geological Survey holds most of their references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

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