Manuscript under review:

Creating a national scale debris flow susceptibility model for Great Britain: a GIS-based heuristic approach (Emma Bee et al.)

On behalf of the authors, I am pleased to submit our response to the anonymous Referee's Comments (RC). We appreciate the time invested in the thorough review of this work and have modified the manuscript based on the suggested comments to the best of our abilities.

Below, I have responded to each suggestion or comment following the indicated structure: 1) Referee's comment (**in bold**), (2) author's response (in blue) and (3) author's changes in manuscript.

We believe that the manuscript benefited considerably from your review and look forward to hearing about the results of the evaluation.

Thank you for your consideration

Sincerely,
Emma Bee, Claire Dashwood, Catherine Pennington and Roxana Ciurean

Referee Comment 1:
1) Pg. 4, line 13: Some GIS based statistical landslide susceptibility assessment have been performed distinguishing between landslide type (see for example Trigila A., Frattini P., Casagli N., Catani F., Crosta G., Esposito C., Ladanza C., Lagomarsino D., Lari S., Scarascia-Mugnozza G., Segoni S., Spizzichino D., Tofani V., 2013 Landslide susceptibility mapping at national scale: the Italian case study. In: K. Sassa, P. Canuti, C. Margottini (eds) Landslide science and practice Vol. 1 Inventory and hazard assessment. Springer, pp. 287-296).

2) Author's response:
Thank you for the reference which we have considered. However, in response to Martina Böhme referee comment 7, in which it was suggested that this section was very long and contains details not relevant to the manuscript, we have shortened this section and rewritten the introduction as described below.

3) Author's change in manuscript:
The term 'debris flow' refers to the rapid downslope flow of poorly sorted debris mixed with water (Ballantyne 2004). Hungr et al. (2014) describe debris flows as "very rapid to extremely rapid surging flows of saturated debris in a steep channel"; widespread in mountainous terrain they are characterised by "strong entrainment of material and water from the flow path". Debris flow initiation can be through a number of mechanisms including shallow landsliding, channel bed mobilisation due to surface water flow, rock fall from a steep bank, seismic activity and are commonly linked to rainfall (Anderson and Sitar, 1995; Hungr et al., 2014; Iverson et al., 1997; Berti and Simoni, 2005; Gabet and Mudd, 2006; Yin et al., 2009).

Debris flows in Great Britain are most commonly found in upland Scotland but also in parts of Wales and the Lake District in England. They occur most commonly following a period of high magnitude precipitation and/or extreme antecedent conditions. According to Nettleton et al. (2005), Ballantyne

(2004) and Cruden (1996) there are two types of debris flow in Great Britain: (a) hillslope or open slope debris flows which form their own path down the valley slopes as tracks or sheets and (b) valley-confined or channelised debris flows which originate in bedrock gullies and are confined for at least part of their length along the gully floor (Fig. 2a and b).

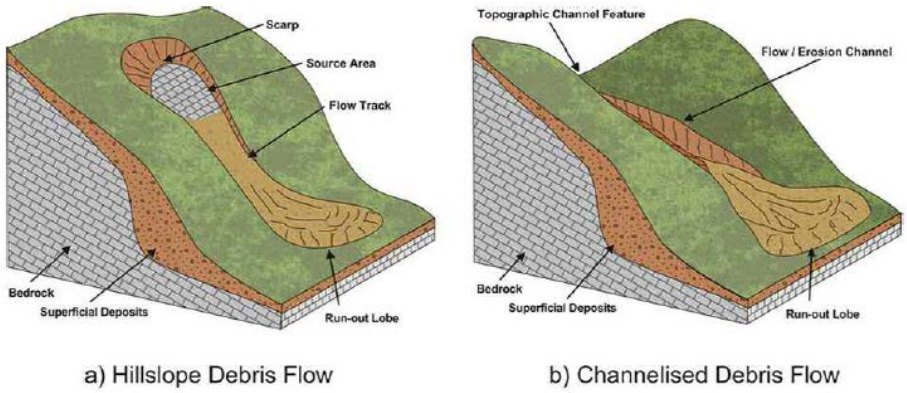


Figure 2: Hillslope (a) and channelised (b) debris flow (Image source: Nettleton et al. 2005)

In Great Britain, the Scottish road and rail networks are recurrently affected by debris flows. In August 2004, two debris flows intersected the A85 in Glen Ogle, north of Lochearnhead, Stirlingshire. Fifty seven people were stranded on the roadway between two debris flows with a cumulative volume of approximately 15000 m3 (Winter et al., 2014) and either left the scene on foot or were rescued by helicopter (Milne et al. 2009). The A85, which normally carries up to 5600 vehicles per day, was closed for four days (Winter et al. 2006). The most widely reported location in Great Britain for debris flow impact on a strategic road is the A83 ‘Rest and Be Thankful’ Pass (British Geological Survey, 2009). Whilst event magnitudes here are generally small, ranging between 200 and 1000 m3 in volume, debris flows have occurred at least on an annual basis over the last 25-30 years (Winter et al. 2014). The road is repeatedly closed in both directions resulting in an 88 km diversion with significant regional economic impact that is regularly reported in the media. Postance et al. (2017) calculated that historic estimates of the economic impact of the 2007 A83 ‘Rest and Be Thankful’ debris flow event totalled £1.2 million over a 15 day closure, 60% greater than previous estimates. Despite the regularity of debris flows on some key strategic routes in Scotland there are no recorded debris flow deaths recorded inland in Great Britain. Recent work by Wong and Winter (2018) suggests the annual probability of a fatality at the A83 Rest and Be Thankful stretch was equivalent to 1 in every 655 years when current mitigation measure are taken into account.

In Great Britain previous studies have concentrated on debris flow susceptibility modelling and hazard ranking in Scotland only. The first regional debris flow susceptibility assessment was the Scottish Road Network Landslides Study (Winter et al., 2005). This was commissioned by the Scottish Executive and conducted by a multidisciplinary working group in response to debris flow events in 2004 that impacted Scotland’s road network substantially. The assessment was calibrated by the working group and then interpreted to derive hazard and hazard-ranking information for the Scottish road network (Winter et al., 2013). Areas of England and Wales also prone to debris flows, such as the Lake District and Snowdonia National Park, were excluded from this assessment. To respond to the needs of national asset managers, decision-makers and practitioners, a methodology was developed to create a high level debris flow susceptibility map that displayed the distribution of likely source areas spatially at national scale. The aim of this study was to identify potential debris flow initiation areas and serve as an indication where further, more detailed regional studies should be carried out. Refining the model with a more detailed DTM and further relevant factors such as slope curvature and upslope contributing area coupled with runout modelling would enable infrastructure, such as roads and railways, in high susceptibility areas to be identified with greater spatial resolution.

Referee Comment 2:
1) Pg.6, Par. 2.2 Predisposing morphological and geological factors: please specify the map scale of the input data (eg. Soil-Parent Material database, GCI, Quaternary Domain Map)

2) Author's response:
The scale of the indicated maps has now been added in the text.

3) Author's change in manuscript:
In order to create a spatial data layer that classifies geology based on its susceptibility to debris flow occurrence, the BGS 1:50,000 scale Soil–Parent Material Database (Lawley et al., 2009) was analysed to determine the character and availability of regolith and to score the material according to its propensity to fail as a debris flow.

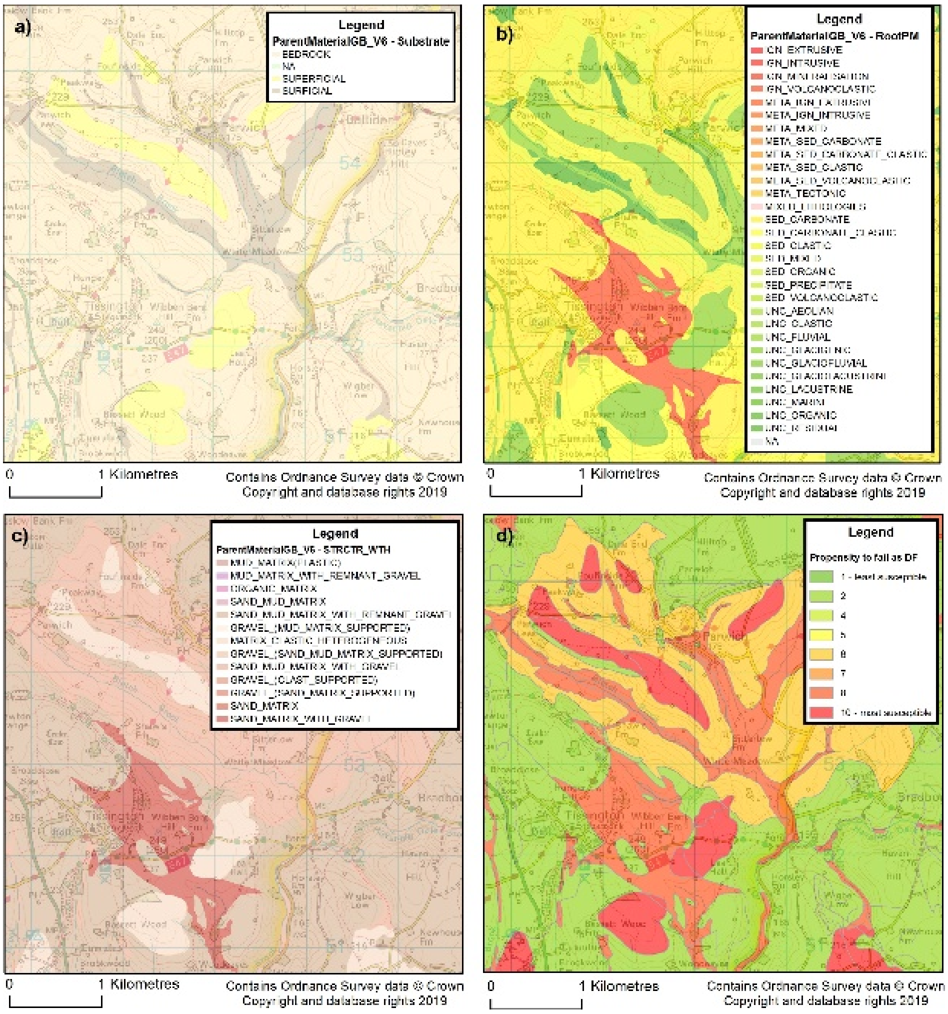
The GCI dataset (fig 5) utilises the BGS 1:50,000 scale permeability datasets for superficial and bedrock geology (Lewis et al. 2006

In order to capture this spatial extent of glacial scouring and the subsequent reduced likelihood of debris flows in affected areas of North West Scotland the 'ice-scoured montane' domain of the BGS 1:625,000 scale Quaternary Domain Map (Booth et al., 2015) was utilised

Referee Comment 3:
1) Pg.7, Figure 4.d: please check the legend

2) Author's response:
The legend for Figure 4d has been corrected.

3) Author's change in manuscript:



Referee Comment 4:

1) Pg.9, Par. 2.2.3, Table 2: In the text "Scores assigned to slopes overlaying a stream channel were increased by a factor of two in the 20 - 30_ and 15 - 20_ categories"; in the table score assigned to the categories are 4 and 6; in the caption "Score increased to 16 or 28". Please check.

2) Author's response:

The text and table headings have been modified to reflect a clearer description of the methodology.

3) Author's change in manuscript:

In-text: Where slopes with angles of 15°- 20° or 20°- 30° coincided with a stream channel, the score was increased to reflect the observations of Innes (1983) and Milne (2008) that channelised debris flows can initiate on lower angle slopes and to denote their higher potential for debris flow initiation than for open hillslopes with equal gradients.

Table 2: Scores assigned to slope angle. Score increased to 6 and 8 (from 4 and 6, respectively) only for slopes with angles of 15°- 20° and 20°- 30° coinciding with a stream channel

Slope angle (°)	0-3	3-15	15-20	20-30	30-32	32-42	43-46	46-50	>50

Score	0	2	4 or 6	6 or 8	8	10	8	6	2

Referee Comment 5:
1) RC: Par. 2.2.3, line 18: "archyrdo tool" instead of "archydro tool"

2) Author's response:
Typo was corrected in the text.

3) Author's change in manuscript:
archydro

Referee Comment 6:
1) Pg.9, Par. 2.23: I suggest to calculate the distribution of slope angle (histogram) in the study area and at the debris flow point (see for example Van Westen, C.J., Castellanos E., Kuriakose S.L. (2008) Spatial data for landslide susceptibility, hazards and vulnerability assessment: an overview. Engineering geology, 102 (3-4), 112-131)

2) Author's response:
Thank you for the suggestion. Representative subsamples of the study area were selected to analyse the debris flow – slope class relationship. For consistency and ease of comparison, these were the same areas indicated in the manuscript in Figure 9 (including the validation site area).

3) Author's change in manuscript:

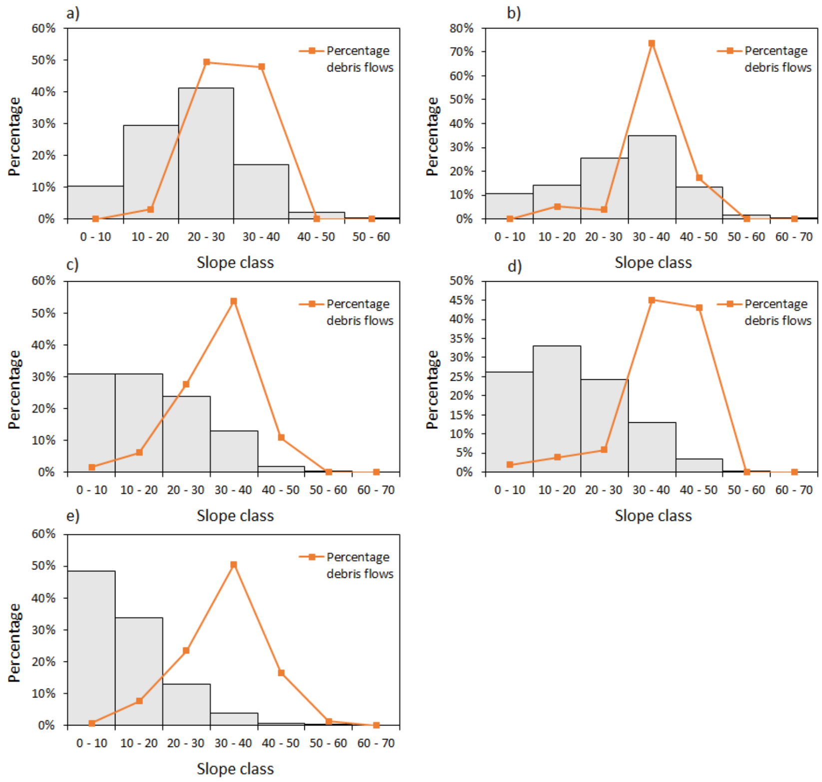


Fig. 11 Relationship between slope angle classes and debris flows. Orange line indicates the percentage frequency of debris flows in a given class. Histogram illustrates the distribution of slope angle classes in a) Rest and Be Thankful area (A = 66 km^2; number of debris flows, N = 67); b) Glen Coe,

Scotland (A = 45 km^2; N = 76); c) Lake District, England (A = 536 km^2; N = 65); d) Snowdonia, Wales (A = 88 km^2; N = 51); e) Cairngorm Mt., Scotland (A = 817 km^2; N = 691). See also Fig. 9.

Figure 11 illustrates the relationship between slope angle and debris flows. In all indicated areas, most debris flows initiations within the inventory are observed on slopes varying between 30° and 40°, in line with the findings of Ballantyne (2004).

Referee Comment 7:
1) Pg.14, Par. 3, line 14: Results and discussion: please enter "frequency ratio" formula

2) Author's response:
Changes have been made in the text and the formula for frequency ratio has been added.

3) Author's change in manuscript:
The frequency of landslides in a desired class (FR_i) is computed as the ratio between the frequency of landslides in the F_i area (PL_i) and the frequency of the F_i area (PF_i).

$$FR_i = PL_i/PF_i \qquad \textbf{(Eq. 2)}$$

where PL_i is the ratio between the area of landslides in the F_i area and the area of landslides in the study area; and PF_i is the ratio between the area of the F_i area to the entire study area (Li et al., 2017). A frequency ratio FR_i larger than 1 indicates that the ith class of factor F (F_i) favours the occurrence of landslides while the opposite is indicated for FR_i smaller than 1.

Referee Comment 8:
1) Pg.15, Par. 3, line 12: In the text "Vakhshoori and Zare, 2017"; in References "Vakhshoori and Zare, 2018"; please check

2) Author's response:
The date in the text was corrected.

3) Author's change in manuscript:
Although it cannot reveal the actual uncertainty of spatial prediction patterns (Vakhshoori and Zare, 2018), it provides a good estimate of the model accuracy and a common base of comparison between models.

Referee Comment 9:
1) Pg.16, Par. 3, line 15-18: in order to consider the heuristic model as the most appropriate on the study area, I suggest to compare it with a statistical model (bivariate/multivariate; see for example Lee S., Min K., 2001 Statistical analysis of landslide susceptibility at Yongin, Korea. Environmental Geology, 40, 1095–1113; Reichenbach P., Rossi M., Malamud B.D., Mihirb M., Guzzetti F., 2018 A review of statistically-based landslide susceptibility models. Earth-Science Reviews 180 (2018) 60–91).

2) Author's response:
A section has been added in the text to detail why the proposed approach was the most appropriate one given the available input data and lack of a specific debris flow inventory.

3) Author's change in manuscript:

At the start of this study a separate inventory for debris flows was not available and so statistical methods of susceptibility mapping were not possible. A national high resolution DTM was not available to allow for a physically based model and so a qualitative heuristic method was used to take advantage of the available data and the broad range of existing studies that had already been undertaken.