Rainfall thresholds and susceptibility mapping for shallow landslides and debris flows in Scotland

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1. Introduction

The spatio-temporal occurrence of landslides is determined by: (i) factors related to slope susceptibility or 'where' landslides can occur, such as geomorphology or lithology; and (ii) factors related to 'when' landslides can occur including by the exceedance of antecedent and initiation rainfall thresholds. In this study, an inventory of 75 landslides in mainland Scotland (70,100 km^2) for the period 2004 to 2016 is used to construct a landslide susceptibility map using a logistic regression model and rainfall thresholds are determined using a binary classification and receiver operating characteristic (ROC) analysis [1]. Susceptibility is calculated for individual hillslope sections and thresholds are derived from a 5 km^2 resolution precipitation radar. These assessments are combined to produce a hazard map and to identify the strategic road network segments that are likely to be affected by landslides.

2. Method

A. Terrain Susceptibility

Logistic regression model trained and tested (70 - 30 split) using 30-fold cross validation. The mean coefficients are then used to model the susceptibility of all hillslopes in Scotland. The model factors include:

- **Hillslopes**: hydrometric slope units with mean area of 0.21 km^2; susceptibility is modelled for each hillslope unit.
- **Slope Max & Elevation Range:** continuous variables.
- **Slope**: classes for median slope angle (0 - 10º, 10 - 20º etc).
- **Aspect**: classes for mean slope aspect (NW - NE etc).
- **Melton Ratio (MR)**: classes for topographic roughness index.

5 m^2 digital elevation model.

- **Soil Parent Material:** soil material and particle size (mm) classes. Silty clay < 0.002. Silt < 0.06. Silty sand 0.002 - 0.06. Sand clay silt 0.06 - 5.0 + larger stones. Fine sand 0.25 - 2.0. Peat soil.

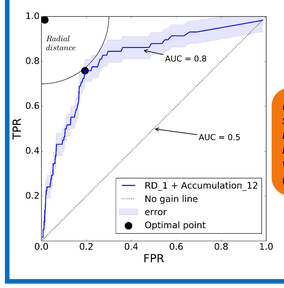
1 km^2 soil parent material model [2].

The model reference categories are the classes with the lowest number of landslides (= 1): slope (30 - 40º), NE - SE, MR (0.9 - 1.2) and Silt slope materials.

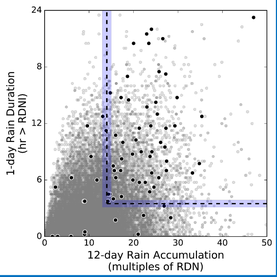
B. Trigger Thresholds

Determined using binary classification and 'optimal point' selection in an ROC analysis (left); optimal point maximises landslide detection. Rain radar and monthly Rainy-Day-Normal (RDN) provides spatio-temporally normalised rain. The combination of 1-day rain duration and 12-day rain accumulation provides the most robust threshold detecting 68 % of landslides (right).

Annual trigger frequency per cell is: $\mathrm{ATF} = p(TH) \times p(LS|TH)$



Repeat random sub-sampling of the rain record indicates threshold variance is ±10% (blue shading)



C. Landslide Hazard

Approximated by the product of terrain susceptibility and the greatest annual triggering frequency for each hillslope unit (results B).

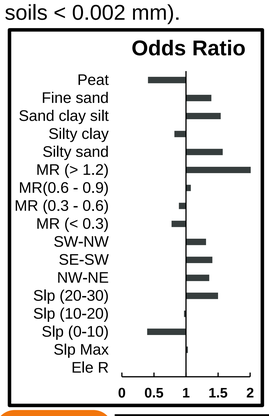
For road network segments, hazard is the product of the sum of the susceptibilities and the greatest triggering frequency from the intersecting hillslopes. These are then converted to normalised probabilities to ensure consistency with the mean recurrence interval of the landslide inventory (6 Yr $^{-1}$).

A debris flow which occurred on the 18th August 2004 deposited 400 tonnes of material on the A85 strategic road at Glen Ogle. The road was closed for four days with an estimated cost of £160 - 260 thousand due to disrupted traffic alone [3]. This is just one example of ~40 such incidents, of similar magnitude, which have occurred in the period 2003 - 2016.

3. Results

A. Terrain Susceptibility

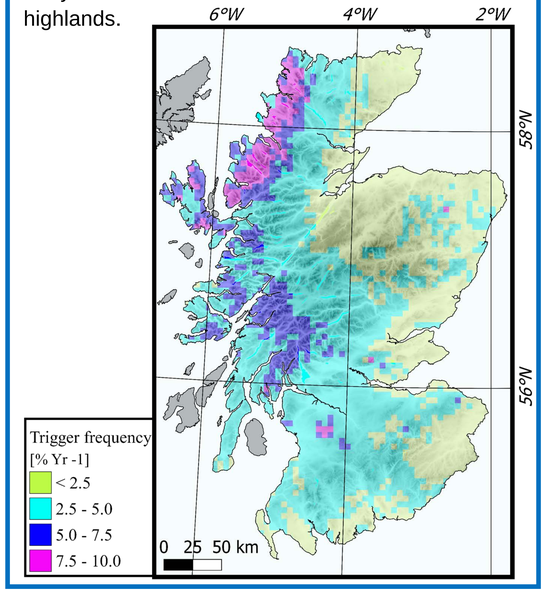
Odds ratio shows the change in the probability that a slope is susceptible for each different factor class or unit increase. Odds of 1 indicate no change. Positive and negative odds show increasing and decreasing probability, respectively. Grey shaded areas are not included as they have factors not associated to any landslides (clay soils < 0.002 mm).



p is the cut-off value for each colour band. Band accuracy % shows the proportion of slopes correctly predicted as landslide or non-landslide [4].

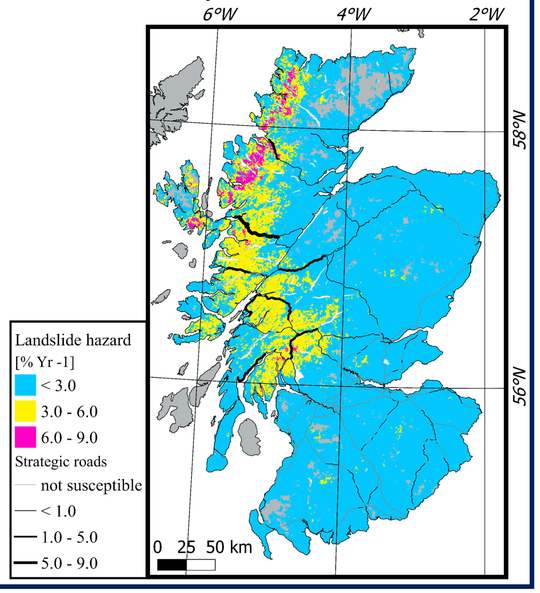
B. Annual Trigger Frequency

Trigger frequency is highest in the North and West of Scotland. Grey shading shows the terrain elevation (max 1350 m asl). Lower frequencies in the east, including the Cairngorm mountains, are likely due to the rain-shadow effect of the west highlands.



C. Landslide Hazard

Landslide hazard is greatest for roads in central west Scotland. There is higher landslide hazard in the north west Scotland but with fewer adjacent roads. However, not all landslides will disrupt road segments and therefore hazard is likely to be overestimated.



Conclusions

This work presents the initial results of a study combining a landslide susceptibility model and initiation thresholds. A similar approach has been demonstrated in other landslide prone regions and is shown to improve a landslide early warning system [4]. For Scotland, landslide susceptibility is most influenced by fine – coarse grain sand materials, high terrain roughness and median slope angles of 20 - 30º. Triggering frequency is greatest in the west and is influenced by topographic effects. The landslide hazard on road segments may be readily converted to monetary costs where data on diversionary routes and travel costs are available [3]. Such assessments will be beneficial to road network operators who must allocate mitigative measures on a cost-benefit basis. In order to improve these landslide hazard assessments, requires further considerations for the road damage or deposition potential of landslides.

Contact / Acknowledgements

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[1] Foster, C., Gibson, A. & Wildman, G., 2008. The new National Landslide Database and Landslide Hazard Assessment of Great Britain. In *First World Landslide Forum*. Tokyo, Japan, pp. 203–206.

[2] Lawley, R. & Smith, B., 2008. Digital Soil Mapping at a National Scale: A Knowledge and GIS Based Approach to Improving Parent Material and Property Information. In *Digital Soil Mapping with Limited Data*. Dordrecht: Springer Netherlands, pp. 173–182.DOI:10.1007/978-1-4020-8592-5_14

[3] Postance, B. et al., 2017. Extending natural hazard impacts: an assessment of landslide disruptions on a national road transportation network. *Environmental Research Letters*, 12(1), p.14010.DOI:10.1088/1748-9326/aa5555

[4] Segoni, S. et al., 2015. Integration of rainfall thresholds and susceptibility maps in the Emilia Romagna (Italy) regional-scale landslide warning system. *Landslides*, 12(4), pp.773–785.DOI:10.1007/s10346-014-0502-0