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Development of Rainfall Thresholds for Landslides in Wales and the Application to Geotechnical Risk Management of Transport Infrastructure

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Abstract

Wales has experienced some of the most catastrophic landslides in UK recent history. Landslides on or adjacent to the transport network in the last five years have caused disruption and, in one event, led to a fatality. February 2020 saw record-breaking rainfall with multiple landslides impacting transport infrastructure. Extreme weather events are anticipated to become more frequent and the risk of failure of ageing earthworks is likely to increase. Adaptation to manage maintenance and the impact of climate change are key aims of the Well-being of Future Generations (Wales) Act 2015 and Welsh Transport Strategy 2021. As part of the resilience planning, Welsh Government are investigating whether antecedent and forecast rainfall data can be used to alert regional safety patrols of an elevated risk of slope failure. In the first study phase, the authors have established rainfall intensity-duration thresholds for landslides at study sites, through analysis of landslide events and associated rainfall parameters calculated from rain datasets. This paper presents the approach for preparing rainfall intensity-duration graphs and thresholds. The challenges and opportunities for future project phases are described.

Keywords: Slope Stability, Landslide, Geotechnical Risk Management

1. Introduction

Wales has a generally moderate to high landslide susceptibility (Wilde et al., 2018) and the South Wales coalfield has one of the highest UK landslide densities (Bentley and Siddle, 1996). The BGS indicate that their National Landslide Database records 2735 landslides in Wales, of which 183 are dated (BGS, pers. comm. 2021). Most inland landslides originated during periglacial conditions and whilst some are dormant, others have been reactivated by rainfall or human activities (Lee et al., 2000). Failures have also occurred in spoil tips and infrastructure earthworks. After water-induced failures, Welsh Government observations indicate that the most common highway earthwork instability issues concern old over-steepened slopes.

The road network in Wales is 34,850km in length with motorways and trunk roads accounting for 5% of classified roads but 32-37% of journeys (Welsh Government, 2019; StatsWales). Road traffic increased by around 45% between 1993 to 2019 (Welsh Government, 2020). In 2008 there was 912miles (1468km) of railway managed by Network Rail in Wales (NR, 2008), of which the Core Valley Lines (215km), was transferred to Transport for Wales in 2020 (Amey-Keolis, 2020). Much of the motorway and trunk road network is less than 60 years old but the rail network and many non-trunk roads are much older and less likely to be engineered. In the late 1980s it was reported that many motorway earthworks in England and Wales were of an age where instability may occur (Perry, 1989). Now, 30 years later and with weather extremes becoming more frequent many infrastructure earthworks in Wales may be susceptible to instability unless engineering interventions have been undertaken.

Landslide events in the last five years that significantly impacted the network are shown in Table 1. The events were associated with intense or extended antecedent rainfall, supporting empirical records that indicate landslide movements occur more frequently after heavy and/or prolonged rainfall both in Wales and the wider UK (Lee and Brunsden 2000; Siddle and Bentley, 2000; Pennington et al., 2015; Mair 2021). Annual rainfall in Wales varies from <1000mm in coastal regions and close to the border with England, to >3000mm in Snowdonia. Daily rainfall >50mm occurs every other year and October to January are the wettest months (Met Office 2016).

Adaptation to manage the impacts of climate change are key aims of the Well-being of Future Generations (Wales) Act 2015 and Welsh Transport Strategy 2021. As part of the resilience, reliability and safety planning, Welsh Government have commissioned a feasibility study into whether antecedent and forecast rainfall data can be used to alert regional safety patrols of an elevated risk of slope failure. The first phase of the project - the determination of tentative rainfall thresholds for landslides for select study sites as well as the challenges and opportunities of applying the thresholds to early warning systems, are described in this paper.

Table 1: Recent landslides on the Wales transport network associated with rainfall.

MM/YYYY	Road/rail route	Event, immediate impact
11/2017	A545 Glyngareth	Supporting slope eroded, road closure
10/2018	A484 Cwmdaud	Slope failure above road, fatality, road closure
	A5 Bethesda-Capel Curig	Landslide, closure of trunk road
	A470 Bwlch Oerddrws	Embankment failure, trunk road unsupported
05/2019	A458 Cwm Cewydd	Cutting failure, partial blocking of trunk road
	A470 Bwlch Oerddrws	Adjacent slope failure, trunk road closure
08/2019	A40 Trecastle-Halfway	Landslide, closure of trunk road
09/2019	A490 Guilsfield	Slope failure above road, road closure
	A4107 Abergwynfi	Landslide debris on road, road closure
11/2019	A44 Goginan	Supporting slope failure, trunk road closure
02/2020	A40 Brecon Bypass	Slope failure above road, trunk road closure
	A479 Pengenfordd	Landslide debris on road, trunk road closure
	A5 Llyn Ogwen-Nant Francon	Slope failure above road, trunk road closure
	Pontsarn-Pontsticill road	Two landslides onto road, road closure
	Mountain Ash	Slope failure above railway, line closure
08/2020	A5 Betws-Bethesda	Debris flow on road, trunk road closure
12/2020	B4301 Carmarthen	Slope failure below road, road closure
09/2022	A498 Capel Curig-Beddgelert	Debris flow on road, road closure

2. Method for establishing rainfall thresholds for landslide events in Wales

Drawing upon the positive correlation between rainfall and landslide activity, empirical approaches aim to establish rainfall thresholds for landslides by applying statistical analyses to landslide and rainfall datasets. Rainfall intensity-duration (RID) thresholds are one such approach which quantify the landslide triggering rainfall condition. In an ideal case, the threshold separates conditions which do and do not result in landslides. Both landslide events and non-events (rainfall conditions which did not result in landslides) are needed.

Winter et al., (2019) showed that it was possible to determine tentative RID thresholds for debris flow events in Scotland, provided a number of prerequisites were met in relation to knowledge of the timing of the event and coverage of rainfall data. With debris flows a common mode of failure affecting the transport network in Wales (Table 1) and with a network of 148 NRW raingauges recording 15-minute interval rainfall data, it was considered that there was adequate inventory to trial the determination of RID thresholds for landslides in Wales. The work represents what the authors understand to be the first derivation of RID thresholds for landslides in Wales.

Six study areas were selected that represent a range of surface, sub-surface and climatic conditions (Figure 1, Table 2). Each site has; 1) potential to impact a transport route in the event of a landslide, or is otherwise significant in terms of size, composition or triggering (i.e., rainfall) mechanism, 2) a nearby raingauge, 3) landslides which have occurred/potential for further failures, 4) known mechanism(s) of failure, 5) inspection regime to identify landslide events. The hydrology of the sites are broadly comparable in that watercourses dissect the valley sides flowing to the valley floor and mapping indicates springs on the valley sides.

15-minute frequency rainfall data was obtained for the period 19/07/2005 to 31/12/2021 from the NRW rainguage closest to each landslide. For the landslides in Table 2 within the rainfall data time period, an estimation of event timing was made. Since the timing is rarely known to within 15 minutes, assumptions on landslide event timing were made: 1) for landslides with a reported event time, the closest 15-minute rainfall reading was assigned, 2) for landslides reported as having occurred 'overnight', the maximum 15-minute rainfall readying between dusk and dawn was used, 3) for landslides reported as having occurred during daylight, the maximum rainfall reading within an hour prior to the earliest report of the landslide was used.

Dusk and dawn times were identified for each date on which a landslide occurred as 30 minutes after sunset and 30 minutes before sunrise, respectively. Non-landslide events were identified as the maximum 15-minute rainfall reading from each day on which a landslide did not occur. Each day was defined from the 00:15 rainfall reading to the 00:00 reading the subsequent day. Rainfall intensity (mm/hr) for all landslides and non-landslide events was defined for durations from 0.25hrs to 3600hrs (150 days), selected to consider a range of antecedent conditions. Using the above approach, RID graphs were plotted for landslide and non-landslide events at each study site using the approach of Winter et al., (2019).

Figure 1: Study site locations. Base map: OpenStreetMap contributors 2022.

Table 2: Study sites summary characteristics and landslide events. [1]BGS landslide domain. *Month unknown.

Site	**1. Tylorstown, Wattstown**	**2. A469 Troedrhiw-fuwch**	**3. A466 Llandogo to Tintern**	**4. A40 Brecon Bypass**	**5. A470 Bwlch Oerddrws**	**6. A5 Capel Curig to Bethesda**
Setting	Colliery spoil tips on Rhondda Fach valley sides	West side of Rhymney valley, railway at toe	West side of Wye valley	Cutting in south side of Usk valley	Toe of north side of valley	North/east side of Nant Ffrancon valley
Geology	Colliery spoil over interbedded mudstone, siltstone & sandstone	Glacial till, landslide deposits over interbedded sandstone, mudstone & siltstone	Alluvium, head over sandstone	Hillwash over interbedded siltstone, sandstone & mudstone	Variable head, glacial, alluvial & river deposits over mudstone/ siltstone, sandstone/ tuff with intrusions	Variable head, alluvial & glacial deposits over siltstone
Vegetation	Grass/scrub, sparse trees	Grass/scrub	Dense trees	Pine trees, scrub	Grass/scrub, sparse trees	Sparse
Landslides (mm/yyyy)	Tylorstown: 02/2020 Wattstown: 12/2020	01/1902, 03/1905, 05/1906, 1906-1910, ??/2004, 02/2014, 02/2020	02/2007, 01/2008, 11/2012, 10/2013, 2014*	02/2020, 02/2021	01/2005, 09/2009, 10/2018, 03/2019	08/1879, 08/1900, 04/1960, 09/1983, 11/2005, 12/2013, 10/2018, 02&08/2020
Mode(s) of failure	Rotational slips + debris flows	Deep rotational + debris flows	Debris flows, washouts, rock falls	Debris flows	Burst failures, channelised debris flows	Debris flows
Domain[1]	N/A	6	2	2	2	5
NRW rainguage (direction)	Nant-yr-Ysfa 2.5km E	Rhymney 5km N, Ty Fry 7km S	Collister 18km SW	Brecon, 1km W	Rhyd Y Main, 5km NW	Bethesda at W, Cwm Dyli 5-7km S

Figure 2 shows an example of the analysis results for the timed landslide events (blue, yellow and green diamond symbols) and non-landslide events (grey and black circles) for study site 6 (A5 Capel Curig to Bethesda) as a RID graph. Lower bound and tentative thresholds are shown. Figure 3 shows the landslide events for all study sites.

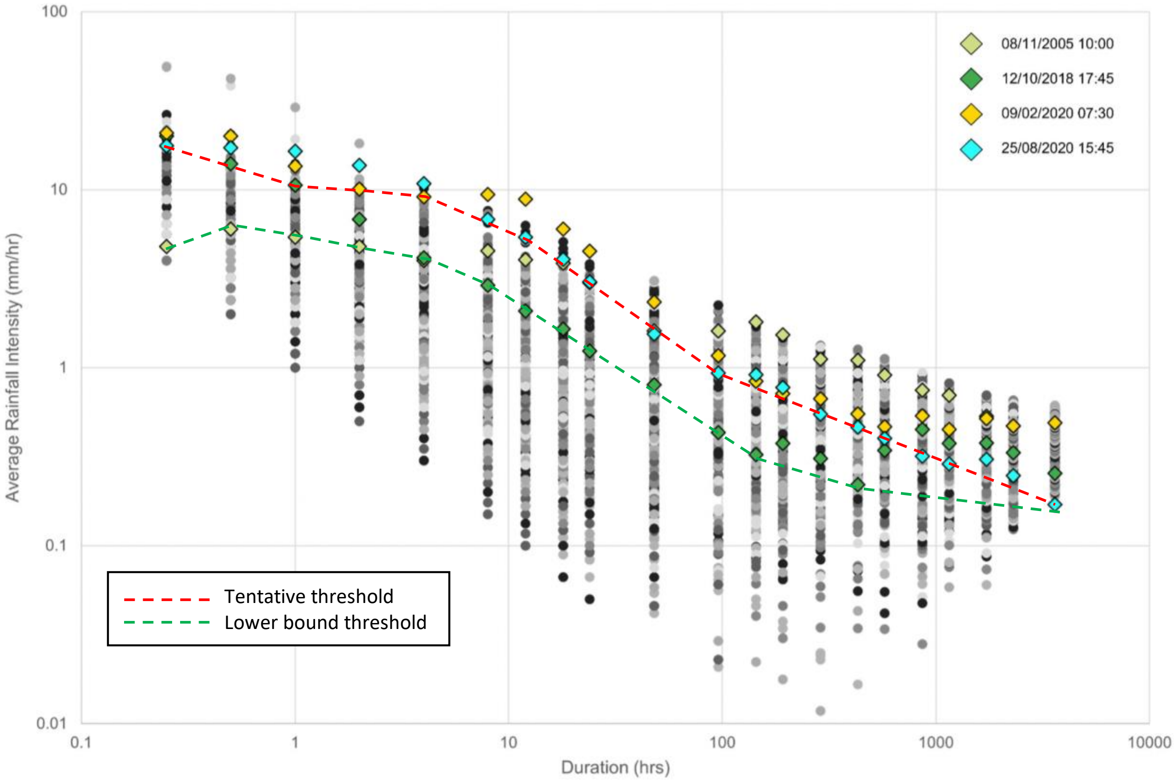

Figure 2: Rainfall intensity-duration (RID) graph for landslide and non-landslide events at study site 6.

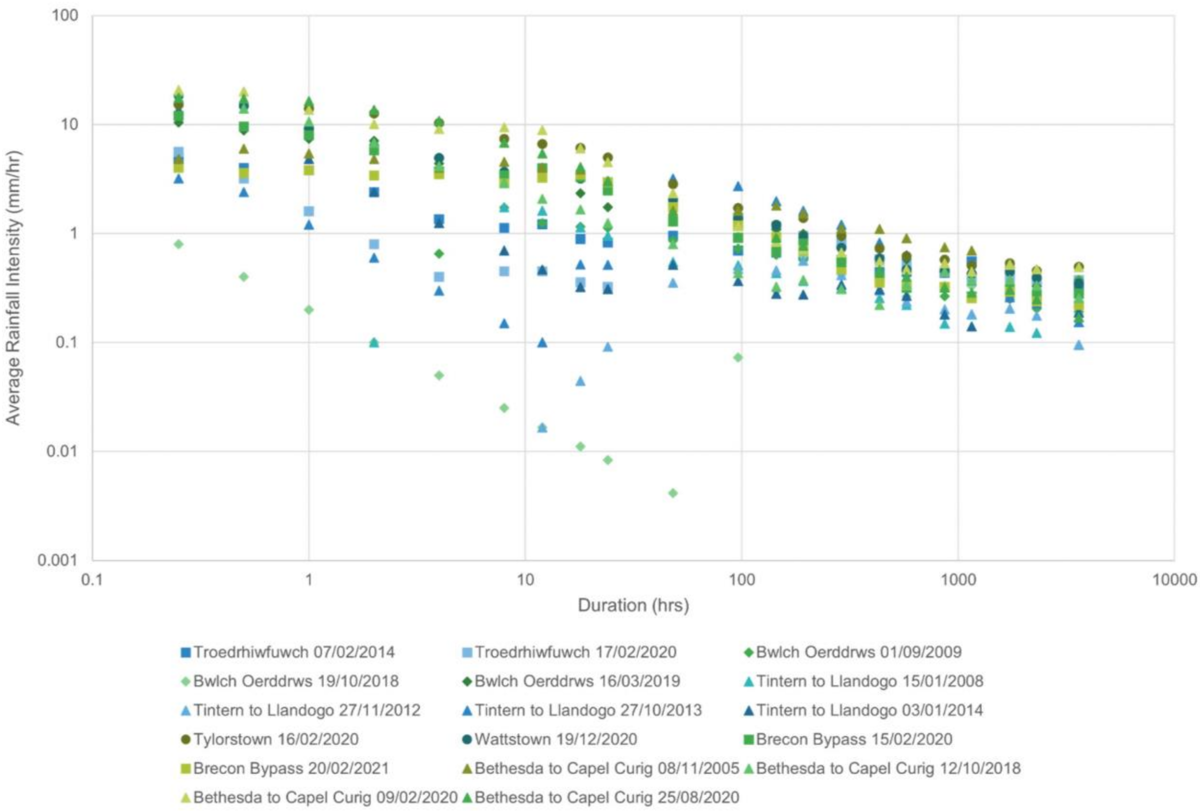

Figure 3: RID graph for all landslides at all study sites.

3. Discussion of preliminary results

17 landslide events could be considered within the date range of the available rainfall data (Figure 3). Incomplete rainfall data from some stations prevented the inclusion of a small number of events in the study. Landslide events were found to largely plot at higher rainfall intensities than non-landslide events on the RID graphs (e.g., Figure 2), as expected. However, a distinct separation between events and non-events was not apparent. 'Outlier' data are apparent which plot below the majority of points (Figure 3). The Bwlch Oerddrws October 2018 event represented a failure following a culvert blockage and as such the unique drainage condition and landslide trigger at that site may be reflected in the outlier dataset. When outlier data is excluded, it can be seen that the RID lines/curves are similar in shape and broadly parallel to one another. There is no clear trend or grouping for certain climatic, surface or sub-surface site conditions.

Figure 4 shows the RID data plotted with respect to existing threshold studies or trigger thresholds used in the UK. The tentative threshold of Winter et al., (2019) for debris flows in Scotland lies generally at the lower bound of the landslide events. At the higher intensities, the dataset lower bound lies between the rainfall thresholds (25mm in 24hrs or 12mm in 3hrs) used to activate warning signs on the A83 in Scotland. The lower bound is broadly consistent with the rainfall threshold (40mm in 24hrs) used to prompt coal tip inspections by the Coal Authority. Both the adverse (30-39.9mm in 3hrs) and extreme (>40mm in 3hrs) weather convective rainfall thresholds used by Network Rail to manage train speed and service plot at the upper bound of the dataset. 50mm rainfall in 24hrs (expected every other year in Wales), equivalent to an average intensity of approximately 2mm/hr, plots at around the lower bound of the dataset.

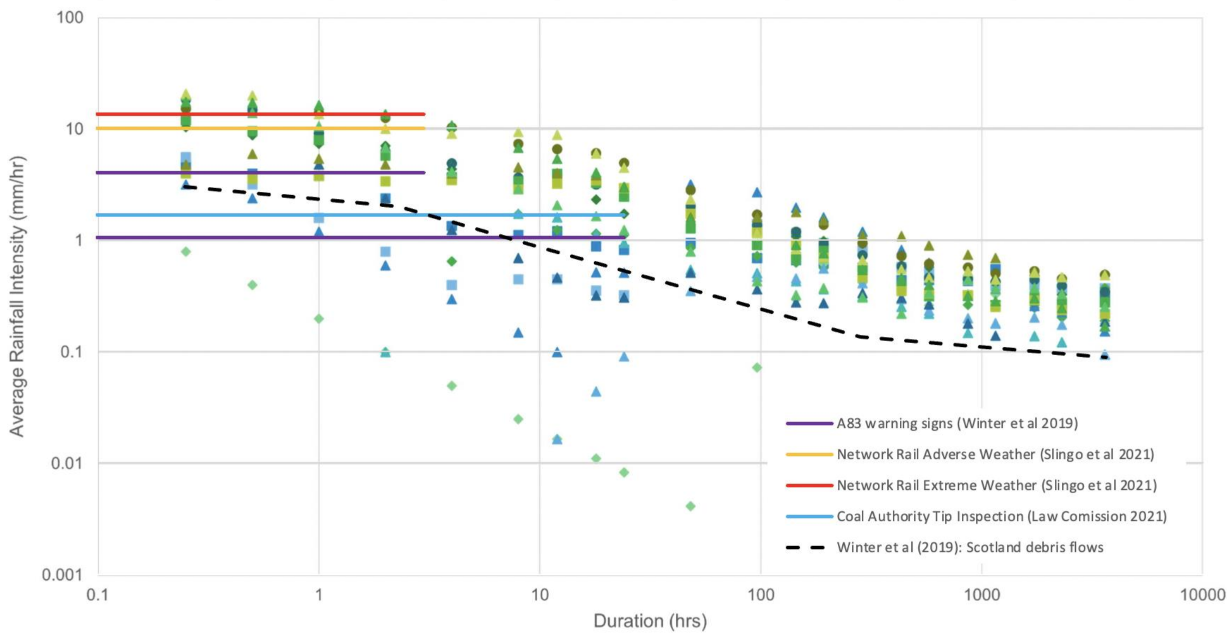

Figure 4: Rainfall thresholds indicated by existing studies and this study. Symbols as Figure 3.

4. Preliminary considerations for application of rainfall thresholds to landslide early warning systems

For a RID threshold (e.g., lower bound) to be effectively utilised in the management of slope failure risk on a transport network, a number of challenges must be considered and the assessment of those factors will form part of future project phases. The themes include: 1) the format and implementation of the final product 2) stakeholder identification, engagement and attitudes to risk, 3) monitoring and communication of warnings/ alerts, 4) consideration of regional variations in surface and sub-surface conditions, 5) capture and databasing of landslide inventory (historic and recent), 6) on-going refinement of the RID thresholds and modelling.

It is likely that organisations will need to collaborate for monitoring, forecasting and action plan implementation. Any system should be easy to implement and automated where possible, likely making use of GIS for inventory databasing and hazard zoning, but importantly the analyses will require human validation. Actions might represent a scale of escalating thresholds from awareness through to pre-emptive maintenance or perhaps more onerous decisions such as infrastructure closures. Local knowledge of route inspection and management staff will remain key in prioritising and appraising actions, with thresholds complementing existing risk management strategies. Continual appraisal of thresholds will be required to improve accuracy and reliability.

A critical part of the next phase will be the trialling and refinement of the tentative thresholds over a period of 12-24 months with identification and evaluation of rainfall events that approach or exceed the thresholds. In addition, there will be a focus on stakeholder engagement to aid collating additional landslide and/or raingauge inventory and to seek feedback on the practical application of the thresholds to early warning systems. There is currently insufficient information upon which to develop meaningful probabilistic thresholds, however this may form part of a future project phase once additional inventory is collected and analysed.

5. Conclusions

The study has demonstrated that it is possible to prepare tentative deterministic rainfall thresholds for landslides. The trends are broadly consistent with existing threshold studies for similar landslide mechanisms. It is recognised that inaccuracy in the thresholds is sourced predominantly from the absence of a large number of landslides with known failure times and to a lesser extent, the completeness of the rainfall datasets. Whilst this study has shown how assumptions can overcome the limitations, further inventory is required to improve the reliability of the thresholds and the confidence in any application to risk mitigation strategies. With such a high density of landslides in close proximity to infrastructure in Wales and with future climate extremes anticipated, it is concluded that increasing and improving inventory is valuable to enable application of RID thresholds.

The next phase of the project will seek to develop the landslide inventory and engage with managers of transport network geotechnical assets to understand how thresholds might be used as part of asset management/ landslide risk management. In the long-term, it is anticipated that the approach presented can be coupled with GIS systems and remote sensing techniques alongside traditional inspection methods such as those of DMRB CS 641 to detect change and zone landslide susceptibility. It is clear from this early work that there are potential benefits to a range of stakeholders in Wales whose assets may be impacted by landslide hazards.

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