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Rainfall thresholds as a landslide indicator for engineered slopes on the Irish Rail network

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ABSTRACT

Rainfall thresholds express the minimum levels of rainfall that need to be reached or exceeded in order for landslides to occur in a particular area. They are a common tool in expressing the temporal portion of landslide hazard analysis. Numerous rainfall thresholds have been developed for different areas worldwide, however none of these are focused on landslides occurring on the engineered slopes on transport infrastructure networks. This paper uses empirical method to develop the rainfall thresholds for landslides on the Irish Rail network earthworks. For comparison, rainfall thresholds are also developed for natural terrain in Ireland. The results show that particular thresholds involving relatively low rainfall intensities are applicable for Ireland, owing to the specific climate. Furthermore, the comparison shows that rainfall thresholds for engineered slopes are lower than those for landslides occurring on the natural terrain. This has severe implications as it indicates that there is a significant risk involved when using generic weather alerts (developed largely for natural terrain) for infrastructure management, and showcases the need for developing railway and road specific rainfall thresholds for landslides.

1. Introduction

Rainfall is a common trigger for landslides on both natural and engineered slopes. Statistical data of the frequency of the rainfall levels that trigger these events can be used as an indirect measure to estimate the temporal probability of landslide occurrence (Corominas et al., 2014). These thresholds are usually expressed as the minimum of a combination of distinct rainfall parameters that needs to be reached in order for a landslide to occur (Reichenbach et al., 1998). Rainfall thresholds can be developed i) physically, based on numerical models (Iverson, 2000; Salciarini et al., 2006) or ii) empirically (statistically), based on analysis of historical landslide events and accompanying rainfall. In relation to natural slope failures, empirically derived thresholds are commonly used (Caine, 1980; Guzzetti et al., 2007, 2008; Dahal and Hasegawa, 2008; Brunetti et al., 2010; Peruccacci et al., 2017).

A number of studies on both landslide hazard and rainfall thresholds have observed that slope instability is frequently observed adjacent to transport networks (Guzzetti, 2000; Guzzetti et al., 2005; Jaiswal and van Westen, 2009). This is a particular problem for the European rail network that was largely built in the 1800's prior to developments in our understanding of soil mechanics (Gavin and Xue, 2009). As a result, old earthworks are typically poorly compacted with overstep side-slopes and lack adequate drainage, resulting in frequent rainfall-induced failures.

Bunce (2008), Jaiswal and van Westen (2009, 2013) and Jaiswal et al. (2010) considered landslides occurring on transport network earthworks, however they did not compare rainfall thresholds there to natural slopes on a regional or national level. Given the increased focus on safety and improved reporting procedures, many infrastructure managers are developing databases of failure incidence with relatively detailed information becoming increasingly available. This paper uses data collected by the Irish Railway operator to develop rainfall thresholds for landslides on engineered slopes across the network. These are then compared with regional rainfall thresholds derived for landslides on natural slopes to interrogate whether for a given rainfall event a landslide is more likely to occur on natural or man-made slopes, eventually interrogating the applicability of existing thresholds for natural terrain to transport networks.

2. Study area and data sources

2.1. Study area

The study area comprised of the Republic of Ireland, which covers 70,273 km^2. The area is characterised by relatively uniform low-lying

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central plains surrounded by coastal mountains, with a maximum elevation of 1038 m. Over 65% of the area is underlain by carboniferous limestones, which is especially prevalent across the central plains. Other significant geological structures include outcrops of sandstone in the south western coastal ranges and granite in the Wicklow mountains located to the east of the country. The mountains of Western Ireland are comprised of metamorphic rocks and granite (Holland, 2001). Ireland's geomorphology is characterised by the presence of glacial features such as glacial valleys within mountains ranges, and drumlins and eskers in lowlands. Glaciation has also heavily influenced the quaternary geology, with glacial tills (boulder clays) and glacially deposited sands and gravels covering the majority of the country (Fealy and Green, 2009). Ireland has extensive post-glacial peat deposits, with blanket bogs and raised bogs covering up to 20% of the surface area.

The climate in Ireland is temperate oceanic and is classified as Cfb on the Köppen climate classification system (Köppen, 1948). It is characterised by abundant rainfall that is relatively uniformly distributed across the year and a lack of temperature extremes. The major influence on the climate is the Atlantic Ocean to the west with the majority of rainfall coming across the South West. Mountains cover the majority of the Western and Southwestern coast, which reduces the impact of these weather systems on inland areas. As a result, average annual rainfall reduces from between 1000 and 1400 mm in the west to between 750 and 1000 mm on the East coast, with the exception of wetter mountainous areas. The rail network is concentrated on the East coast and the midlands, with a small number of discreet rail termini located on the wetter Western coast. Although the total annual rainfall is relatively high, it is spread over a large number of rainy days, resulting in relatively low rainfall intensities. For comparison with other rainfall threshold study areas, the highest hourly total rainfall ever recorded in Ireland was 52.2 mm, a value easily surpassed in other mid-latitude European climates or monsoonal climates.

The railway network in Ireland extends to over 1700 km of tracks and contains over 3500 earthwork assets, comprised of cuttings and embankments of varied length. As the network mostly extends through the central plains, the vast majority of the cuttings and embankments are composed of local tills and glacio-fluvial sands and gravels. In short segments, where the railway lines passes through mountainous areas, rock cuttings are common. In hilly areas and in the midlands where the network crosses bog land embankments were constructed from borrowed material (usually tills or gravels). As the majority of the network was constructed in the 1800s, most of the embankments were constructed using the construction practice of end-tipping locally available material that results in loosely packed fills with large voids (Nelder et al., 2006; Briggs et al., 2017). The glacial soils used in the earthworks have relatively high friction angles (Lehane and Faulkner, 1998; Long and Menkiti, 2007) that allowed steep slope angles to be achieved. Martinović et al. (2016a) report the average slope angles of earthworks is 40° that is significantly higher than the value of 27° adopted for the earthworks on the modern motorway network in the region.

2.2. Data sources

Landslide data was gathered from Irish Rail (IR), the national operator of the railway network. IR maintains records of geometrical, geological and environmental attributes on all slope assets (earthworks). This data has primarily been gathered by routine visual inspections, however LiDAR has also been used to obtain geometric data. While visual inspections have recorded a relatively large number of landslides along the network (Martinović et al., 2016b), the exact date for most of these landslides is unknown. This is due to a tendency to treat landslides that do not interact with the track as of lesser importance and only recording these failures during the next routine inspection. This management approach is used by other railway operators as well (Bunce, 2008). Most of the landslides used in this study were related to track blockages. For this reason exact dates and in many cases the time of failure event were recorded.

Of those landslides with known dates, those that had no connection to rainfall were discarded. These included i) rockfalls, ii) landslides caused by anthropogenic influence such as toe undercutting, machinery loading, etc. and iii) landslides on assets over soft ground such as peat. The remaining 35 landslides (see Table 1 and Fig. 1) that were included in the study were predominantly shallow translational soil slides, with four failures involving exposed weathered rock and two deep-seated soil slides. In total eight failures occurred on embankments while 27 failures occurred in cuttings. All landslides occurred between 2008 and 2016.

Rainfall data was obtained from the Irish Meteorological Service (Met Éireann). The rain gauge network in Ireland is composed of 25 synoptic stations with hourly precipitation measurements and 423 rain gauges with daily precipitation measurements. Their locations are shown in Fig. 1. Hourly data from synoptic stations is available since 2006, while the entire daily precipitation dataset from rain gauges since their individual activation is available. The total number of rain gauges in Ireland corresponds to an average density of one rain gauge station every 157 km^2. This density makes the study area comparable to Italy where a large amount of rainfall threshold related research has been performed by (Brunetti et al., 2010), validating the quality of data used for analysis.

Average monthly precipitation values for four synoptic stations are plotted in Fig. 2. Two of these stations (Dublin Airport and Carlow) represent the gauges with the lowest average annual precipitation in Ireland, 757.9 mm and 840.2 mm respectively. Two additional gauges recording less precipitation than Carlow exist, but they are not included here as they are both located in Dublin and show values very similar to Dublin Airport. The other two stations (Newport and Valentia) are the gauges with highest 30-year mean annual precipitation, measuring 1607.1 mm and 1557.4 mm respectively. Values plotted for these four stations effectively form the lower and upper bounds of mean monthly precipitation measured on synoptic stations in Ireland. A monthly distribution of landslide frequency on the Irish Rail network over the study period for 35 events considered here is also presented on the same figure. Twenty-two out of 35 landslides (63%) occurred during the wet period between November and January. Fig. 2 also shows that, although being the wettest month on all four stations, only two failures were recorded in October, with the highest number of landslides occurring in November. This indicates the importance of antecedent rainfall as a landslide trigger.

3. Rainfall thresholds for rail network

3.1. Methodology

A number of researchers have proposed rainfall thresholds using a variety of approaches. Guzzetti et al. (2007) grouped empirical thresholds into: i) thresholds that use precipitation data for a specific (critical) rainfall event, ii) thresholds that include antecedent conditions, and iii) other thresholds. In the first group, the most common types of rainfall thresholds are identified as intensity-duration (I-D) thresholds. Other common approaches from the first group are based on the total rainfall, rainfall event-duration (E-D) or rainfall event-intensity (E-I) measures. These thresholds are often normalised using mean annual precipitation (MAP) or rainy day normal (RDN) to remove the effect of local climate thus enabling comparison between thresholds from different study areas. A feature common to all of the minimum threshold types, is that they represent the lowest boundary in coordinate space of a pair of observed rainfall characteristics below which landslides do not occur. The thresholds can be drawn graphically after the rainfall characteristics pairs of values have been plotted, or can be calculated using a

Table 1
Landslide database combined with relevant rainfall characteristics for the area in question.

No.	Date	Cumulative rainfall [mm]	Duration [h]	Average intensity [mm/h]	10 day antecedent rainfall [mm]	30 day antecedent rainfall [mm]	Slope height [m]	Slope angle [°]	Distance to synoptic station [km]	Distance to rain gauge [km]
1	16/08/2008	53.3	8	6.66	105.5	201.7	5.0	48	37.6	17.8
2	16/01/2010	26.6	7	3.80	47.5	86	3.0	55	38.5	3.1
3	31/12/2013	43.2	36	1.20	50.2	90.1	3.0	55	38.5	3.1
4	04/02/2009	52.1	35	1.49	34.4	78.3	13.4	50	4.4	1.1
5	16/11/2009	58.8	63	0.93	52.3	195.3	13.0	35	83.3	4.2
6	09/08/2008	73.9	5	14.77	69.1	89.4	7.9	67	6.5	0.4
7	04/02/2009	37.9	21	1.81	75.7	172.5	4.9	41	59.3	5.0
8	12/11/2009	16.9	5	3.38	30.2	141.2	7.1	48	11.2	11.2
9	13/11/2009	25.0	13	1.92	55.2	192.1	4.8	43	55.6	1.9
10	31/12/2013	42.4	45	0.94	69.9	126.8	15.0	85	94.0	1.7
11	25/11/2009	15.7	10	1.57	152.3	338.5	2.7	42	20.1	6.0
12	16/01/2010	34.9	8	4.37	64.2	151	13.4	62	73.6	5.2
13	07/09/2010	41.9	11	3.81	27.5	50.8	6.3	41	56.6	7.8
14	06/07/2012	22.5	13	1.73	33.7	203.7	12.2	80	73.2	5.1
15	17/10/2012	17.0	3	5.67	28.7	112.1	13.4	50	4.4	1.1
16	25/01/2013	29.4	15	1.96	46.9	103	7.5	72	8.0	8.0
17	27/07/2013	14.5	1	14.48	27.4	37.4	10.2	37	11.8	2.5
18	30/12/2015	43.5	16	2.72	93.5	269.3	4.3	45	84.0	3.9
19	19/11/2009	63.1	40	1.58	82.7	217.6	4.2	47	12.6	3.3
20	14/11/2009	27.2	19	1.43	55.2	192.1	4.0	43	46.8	1.2
21	07/03/2014	19.5	12	1.63	41.9	164.7	7.5	72	8.0	8.0
22	29/12/2015	49.9	12	4.16	187.4	592.6	13.5	67	52.8	10
23	25/10/2013	48.3	8	6.04	83.9	151.5	2.2	53	47.5	0.9
24	22/12/2012	21.6	23	0.94	53.6	119	16.4	67	9.3	4.7
25	13/04/2013	15.2	23	0.66	41	111.8	5.0	60	11.5	11.5
26	04/07/2009	38.2	3	12.75	15	75.2	6.2	49	5.0	0.6
27	23/12/2013	19.8	5	3.96	64.6	68.2	29.6	75	71.6	5.0
28	15/02/2014	25.9	16	1.62	83.6	217.9	5.0	36	83.6	4.3
29	07/12/2015	79.6	37	2.15	100.6	241.2	5.3	35	16.0	12.8
30	05/01/2016	16.9	8	2.12	74.6	159.3	7.0	47	3.7	2.1
31	10/01/2016	22.8	7	3.26	55	166.3	5.2	43	13.5	13.5
32	07/01/2016	19.1	9	2.12	68.7	165.2	5.7	37	25.8	8.2
33	27/01/2016	37.9	8	4.73	57.2	207	3.4	45	21.9	9.0
34	06/11/2014	38.2	22	1.74	69.8	158.5	7.9	54	15.6	6.4
35	14/11/2014	41.5	21	1.97	73	110.4	9.0	52	3.9	1.8

number of different statistical methods (Guzzetti et al., 2007; Vennari et al., 2014; Ma et al., 2015), with the later method being particularly advantageous for the large landslide datasets.

Intensity-duration thresholds are the most common type of thresholds. They are generally expressed by a power law, see Eq. (1).

$$I = c + \alpha \times D^{\beta} \tag{1}$$

where I is rainfall intensity, D is rainfall duration, and c, α and β are fitting parameters.

Rainfall event-duration (E-D) thresholds consider a cumulative measurement of precipitation during a rainfall event. Thresholds using antecedent rainfall aim to take into account not only the critical event rainfall but also the cumulative precipitation in a period preceding it; as antecedent precipitation sets the preparatory conditions for slope instability due to increased soil moisture and groundwater levels. Existing antecedent rainfall thresholds (Crozier, 1999; Glade et al., 2000; Chleborad, 2000; Jaiswal and van Westen, 2009; Huang et al., 2015) show that with increased amounts of antecedent precipitation, the critical event precipitation required to trigger a landslide decreases. Studies have used different durations of antecedent rainfall, with most periods spanning between 3 and 30 days. A common practice is to test the influence of a range of antecedent periods.

When constructing thresholds, some studies plot not only rainfall events that triggered landslides, but include rainfall events that did not trigger any landslides (Zêzere et al., 2015; Gariano et al., 2015; Guo et al., 2016; Giannecchini et al., 2016). The threshold is then constructed in a way to maximise the number of triggering events and minimise the number of non-triggering events above the threshold. In this study, the authors opted not to apply this approach because of data uncertainty with a large number of recorded landslides not being linked to a specific rainfall event, which would compromise the certainty of a rainfall episode being a non-triggering one.

3.2. Critical rainfall event definition

In developing any form of rainfall threshold, identifying the critical triggering rainfall from a continuous series of precipitation data is a crucial process. Critical rainfall represents the rainfall event during or immediately preceding the landslide. The start of critical rainfall is marked by a steep increase in the cumulative precipitation plot immediately prior to the landslide event. However, in practice it can be difficult to precisely identify the exact point of this increase (Melillo et al., 2015). To do this process objectively and uniformly, definitions for determining the start of a critical rainfall event are set in each study, with limits varying significantly depending on the study area's climate conditions.

In this study, the start of the critical rainfall event was defined when hourly rainfall intensity exceeded 1 mm/h. To separate the critical rainfall from the antecedent rainfall, an additional requirement of 12 h with hourly rainfall intensity < 1 mm/h had to be met before the start of critical event. Following this process, the duration D and the average hourly intensity I_{ss} for each of the 35 landslides were collated using the precipitation data from the nearest synoptic station. These are presented in Table 1. The adoption of this relatively low limit is a direct consequence of rainfall patterns in Ireland that is characterised by frequent weak precipitation and low rainfall intensities. Fig. 3 presents the distribution of average intensities and

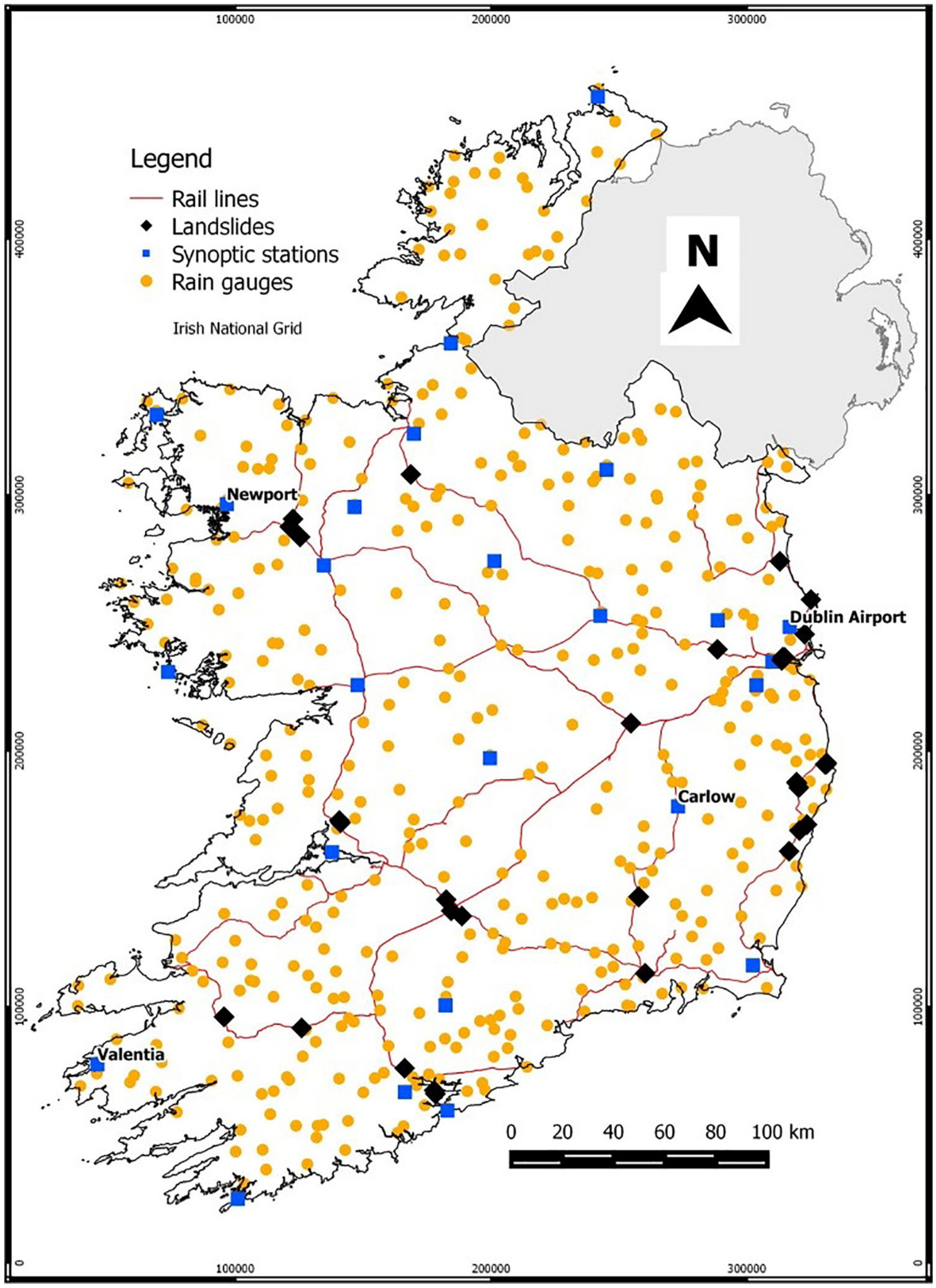

Fig. 1. Geographical distribution of landslides on rail lines and rain gauges in Ireland.

maximum recorded hourly intensities for the 35 critical rainfall events considered in this study. The median values of 2.05 mm/h for average rainfall intensity and 6.18 mm/h for maximum (peak) hourly intensity accurately describe the low intensity of rainfall events in Ireland.

3.3. Values for analysis

While the nationwide network of 25 synoptic stations with hourly readings provides useful data to assist with the initial analysis, there was not sufficient coverage of the country to use only the synoptic data. For that reason, mean intensity values I_{ss} obtained from synoptic stations were modified using daily rainfall readings from the rain stations that were the closest to each failure location, thereby greatly reducing spatial uncertainty in the rainfall values. This was carried out by adjusting the I_{ss} with the ratio of cumulative daily rainfall on rain station (R_{rs}) and synoptic station (R_{ss}), see Eq. (2).

$$I = I_{ss} \times \frac{R_{rs}}{R_{ss}} \quad (2)$$

Due to the uniformity of the terrain over which the rail network operates and the relatively small catchment area of each synoptic station, the durations of a rainfall event spatially vary very little. This allowed the same value of critical rainfall durations to be adopted as those read in the synoptic station data.

Initial intensities from synoptic stations were compared to the modified intensities obtained from Eq. (2) to check if there was much deviation in value. If a significant difference was found between the two approaches it would imply that the readings obtained

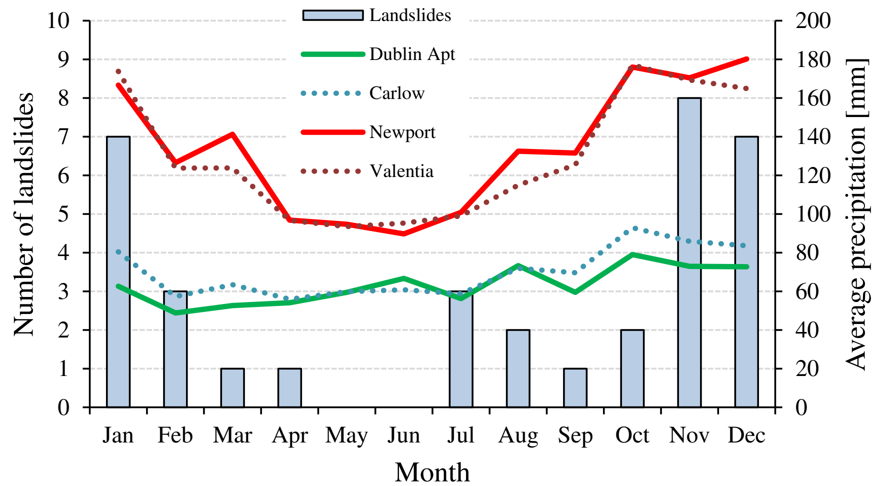

Fig. 2. Monthly distribution of landslides on railway earthworks and average monthly precipitation values for four synoptic station in Ireland.

from the rain stations bear no relation to those from the synoptic stations, thus making the approach obsolete. Fig. 4 presents both the original and modified rainfall intensities obtained by this approach for each landslide used in this study. The mean value of change is 20.71% and median only 1.57%. When taking absolute value of the percentage change (i.e. disregarding if the change was positive or negative), the mean value is 30.56% while the median value is 18.34%. Given the very small absolute intensity values involved, this is considered to be a reasonable deviation, justifying the application of the approach.

Table 1 presented the distance between the landslide event and synoptic station, as well the distance between the landslide event and rain gauge for each landslide. The average distance between landslides and synoptic stations is 34.6 km, while the average distance between the landslides and the rain gauges is only 5.5 km, demonstrating the benefit of using the approach adopted in this study. Further analysis of the rain events show that there is no relation in difference between R and R_{ss} and difference in distances between to synoptic station and rain gauges.

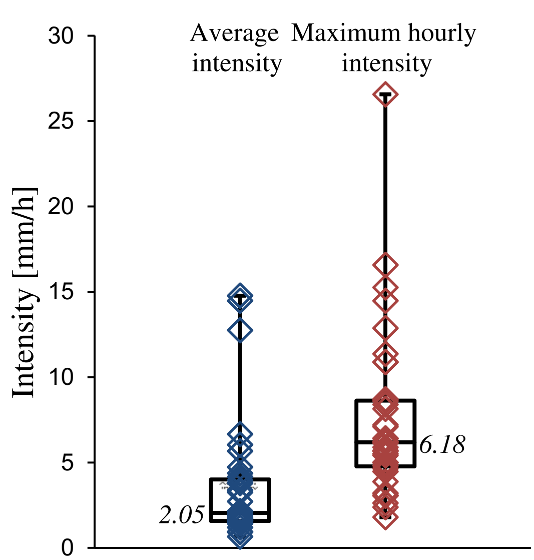

Fig. 3. Distribution of average and maximum hourly intensities for 35 landslides on Irish rail earthworks, with boxes denoting the median value (in text), first and third quartile.

3.4. Results

For the I-D threshold, pairs of modified mean rainfall intensity and duration for each of the 35 landslides were plotted on a log–log scale (Fig. 5). Intensities ranged between 0.66 and 14.77 mm/h, while durations spanned between 1 and 63 h. All plotted events fall into a relatively narrow band with a clear descending trend. A threshold was then graphically determined, forming the lower boundary of all plotted events with the exception of a single outlier. The threshold was set only for the range of durations with a wealth of reliable values, and it ranged between 3 and 70 h. An asymptotic threshold with fitting parameter c ≠ 0 from Eq. (1) was employed to avoid yielding unreasonably low intensities for long durations, an approach recommended by Guzzetti et al. (2007) and successfully applied in the literature (Crosta and Frattini, 2001).The threshold is expressed as in Eq. (3).

$$I = 0.75 + 22 \times D^{-1.5}, (3 \leq D \leq 70) \quad (3)$$

As Fig. 2 suggests, antecedent precipitation can play a significant role in generating the conditions necessary to trigger a landslide. In this study, 10 and 30 day antecedent precipitation values were recorded for each landslide event and each of these characteristics was plotted against the cumulative event rainfall. The results are presented in Fig. 6. Thresholds were constructed by manually locating the lines so that every landslide event is located above the threshold, following the work of Chleborad (2000) and Bunce (2008).

Both thresholds suggest that with an increase in antecedent rainfall, less critical event rainfall is required to trigger a landslide. Two very distinct outliers in the graph for 30 day antecedent rainfall point to the influence of other triggering factors in those particular instances. While there are no outliers in 10 day antecedent rainfall graph, more data is needed to validate the proposed non-horizontal part of the curve. For antecedent rainfall larger than 110 mm (30 days), the trend of diminishing critical event rainfall with the increase in the antecedent rainfall ceases. None of the critical events had <14 mm of accumulated precipitation, which explains the horizontal line for larger durations. While some published thresholds continue the descending trend to the critical event value of zero (Jaiswal and van Westen, 2009; Huang et al., 2015), with discrepancy attributed to differences in the definition of critical rainfall events, the curves here align well with many other proposed antecedent rainfall thresholds (Chleborad, 2000; Bunce, 2008). Occurrence of events with high values of both critical event rainfall and antecedent rainfall, adding to data scatter, can be partially attributed to the fact that the exact time of landslide was not always

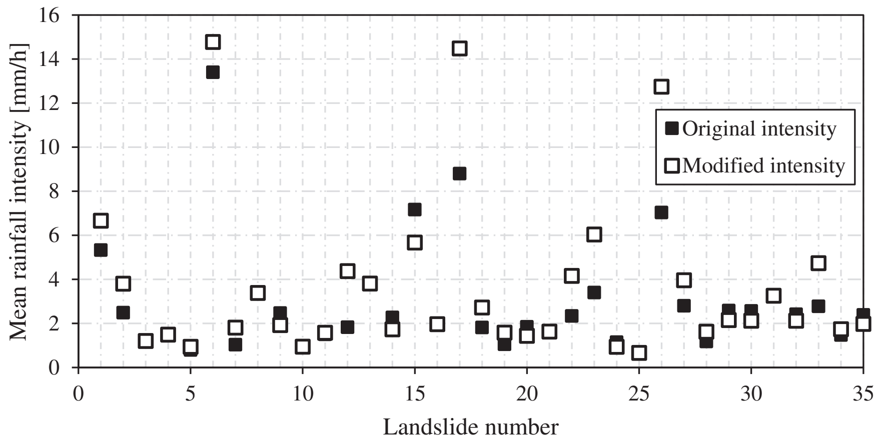

Fig. 4. Distribution of original rainfall intensities from synoptic stations (I_{ss}) and modified intensities (I).

recorded, making it likely that the failure occurred sometimes during the critical rainfall before it reached its full amount.

4. Comparison with thresholds for natural landslides in Ireland

In order to investigate whether landslides occur on engineered slopes at lower rainfall intensities than natural slopes and given no threshold values have been developed for Ireland, a database of rainfall-triggered landslide occurrences on natural slopes was developed. The records used to populate the database were gathered in a manner compatible for the case histories on the rail network. The principal sources of information included the Geological Survey of Ireland's National Landslide Database (GSI, 2016), research papers (Bourke and Thorp, 2005; Long and Jennings, 2006; Boylan et al., 2008; Long et al., 2011) and newspaper reports. While the National Landslide Database contains a reasonably large dataset of landslides with excellent spatial accuracy, the vast majority of landslides have no date recorded. Given the majority of landslides occurred in remote mountainous areas and were usually not reported unless they caused material damage or blocked roads this is unsurprising. As a result the quantity of usable data was much smaller than the actual number of landslides that occurred in the period of interest with only 34 landslides having a reliable time stamp. Rainfall data was collated in the same way as described for landslides on the rail network. Hourly measurements from synoptic stations were obtained for 21 landslides that occurred between 2006 and 2015 along with the daily precipitation measurements from the rain station most relevant in terms of proximity, altitude, orientation and general setting. For the 34 landslides that occurred before 2006 only daily rainfall measurements were available. For the 21 landslides with hourly readings a modified intensity was calculated using Eq. (2). Only these landslide events were used to construct an I-D threshold (Fig. 7), while the entire database was used to construct the critical – antecedent rainfall thresholds. Rainfall thresholds prepared here for natural landslides are somewhat less reliable than for the rail network, as the number of data points may be deemed unrepresentative due the reasons outlined earlier. Local rainfall conditions at higher elevations may also deviate more from synoptic stations and the nearest rain gauges compared to mostly flat terrain associated with a rail network. A strong correlation was nevertheless observed for the thresholds.

Almost all landslides were classified as shallow translational soil slides, with the addition of several debris flows. These were typically formed in the relatively thin colluvium on steep hillsides. While a large number of recent peat failures in Ireland have been reported, only those events where the failure plane formed fully in the mineral soil underlying the very thin top layer of blanket peat were included in this study, in order to allow a meaningful comparison with landslides on the rail network. These slides are classified as peaty-debris slides in a classification approach proposed by Dykes and Warburton (2007) and are often reported as shallow translational slides (Long and Jennings, 2006).

Asymptotic intensity-duration threshold was graphically fitted to the 21 failures that reported hourly rainfall measurements (Fig. 7), expressed by Eq. (4):

$$I = 0.94 + 34 \times D^{-1.5}, (3 \le D \le 70) \quad (4)$$

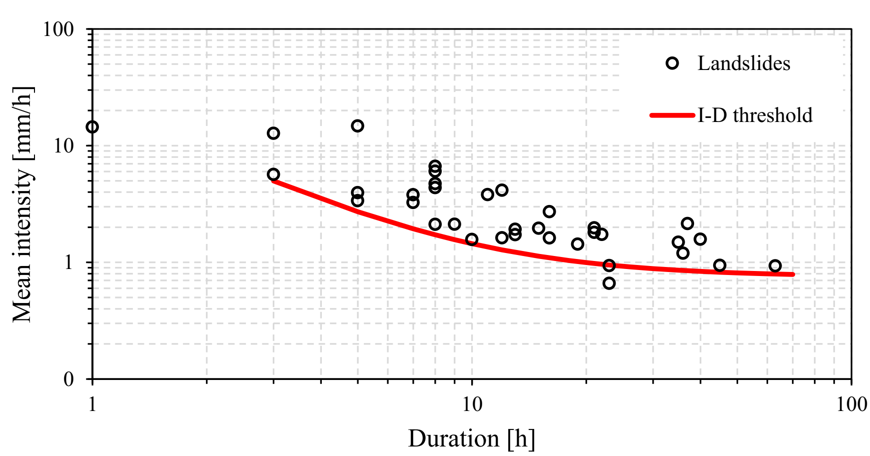

Fig. 5. I-D threshold for landslides on Irish Rail network.

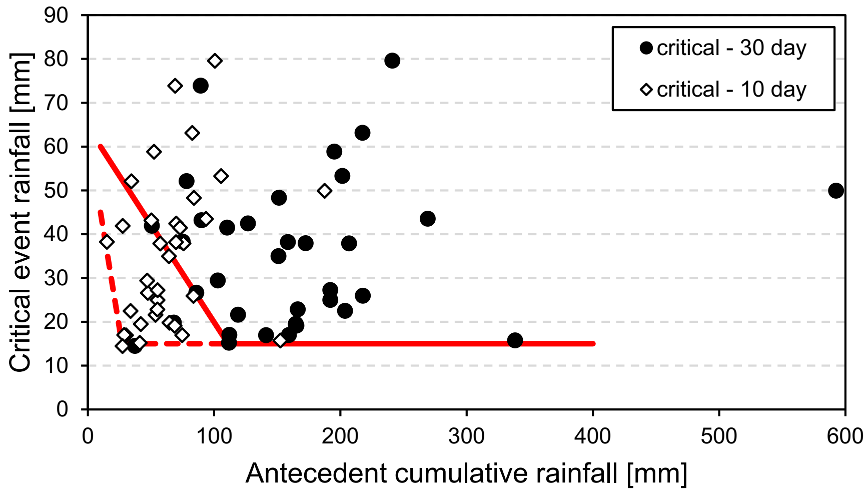

Fig. 6. Critical event rainfall – cumulative antecedent rainfall threshold. Threshold for 10 day antecedent rainfall in dashed red line, threshold for 30 day antecedent rainfall in solid red line.

The threshold established for rail earthworks is plotted on the same graph for comparison. Both curves follow a similar trend, with the natural terrain threshold clearly indicating that a higher rainfall intensity is needed to trigger landslides across all rainfall durations. While the difference between thresholds may seem small, over a third of the rail landslides are positioned below the natural slopes threshold, proving the importance of discerning between natural and engineered slopes. The difference in rainfall intensity required to trigger a landslide varies with rainfall duration, reducing from 50% to 28% as the rainfall duration increases from 5 h to 50 h.

The effect of antecedent rainfall on the rainfall required to trigger a landslide on a railway slope and natural slope is compared in Fig. 8. Two periods for measuring antecedent rainfall were considered, 10 days (Fig. 8a) and 30 days (Fig. 8b). Rainfall events that triggered single and multiple landslides on natural slopes are considered. Both graphs show that for the case of any critical rainfall event, higher antecedent rainfall is needed to enable the triggering of landslides on natural hillsides compared to landslides on railway earthworks. The difference is much more pronounced in the 10 day antecedent rainfall graph. The 10-day graph also exhibits much better grouping of landslide events in the region just above the threshold, and exhibits no outliers, leading to the conclusion that 10 day antecedent rainfall is more suited for the determination of landslide triggering conditions.

One of the reasons for the wide variation in rainfall thresholds worldwide lies in the selection of landslide events. Studies that included single and minor landslide events (such as this study) were shown to result in lower thresholds than studies which included only multiple landslides events (Guzzetti et al., 2008; Brunetti et al., 2010). To investigate this effect, rainfall events causing landslides on natural terrain in Fig. 8 were classified into events that caused a single landslide (the 22 events are represented by open diamond symbols) and multiple events (the 12 events are plotted with full diamond symbols). Unsurprisingly, the mean rainfall intensity data for these events reveal that high rainfall intensities are needed to trigger multiple events. Critical rainfall of at least 30 mm was needed to trigger multiple landslides, and six out of nine events with cumulative rainfall of over 60 mm resulted in multiple events. Consideration of these events shows that they are associated with high mean intensities and large peak intensities suggesting multiple slides are triggered by intense rainfall events. This is an important finding in light of the more intense rainfall episodes being predicted for the future climate in the 21st century (Sweeney et al., 2008; Gariano and Guzzetti, 2016). Another interesting feature is that all but one of these events were recorded in conditions with relatively low antecedent rainfall and eight out of twelve occurred in what Fig. 2 suggests to be a drier period countrywide (February–September). This can be partly explained by the drying and

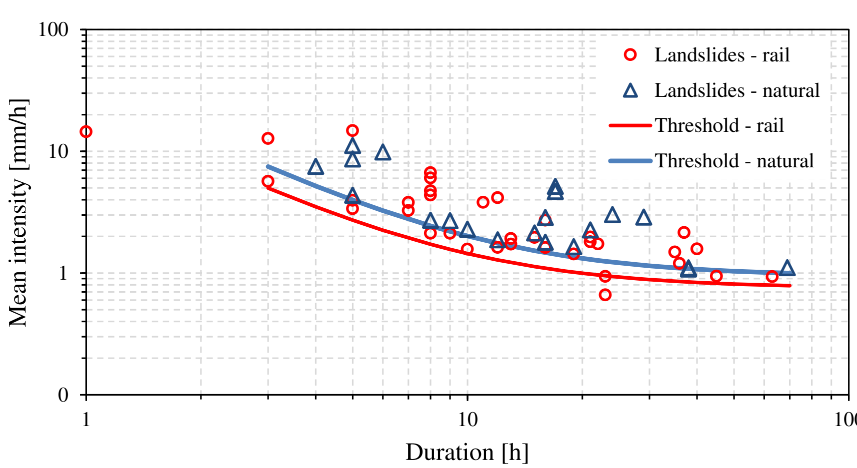

Fig. 7. I-D rainfall thresholds for engineered slopes for rail network (red line) and for landslides on natural terrain in Ireland (blue line).

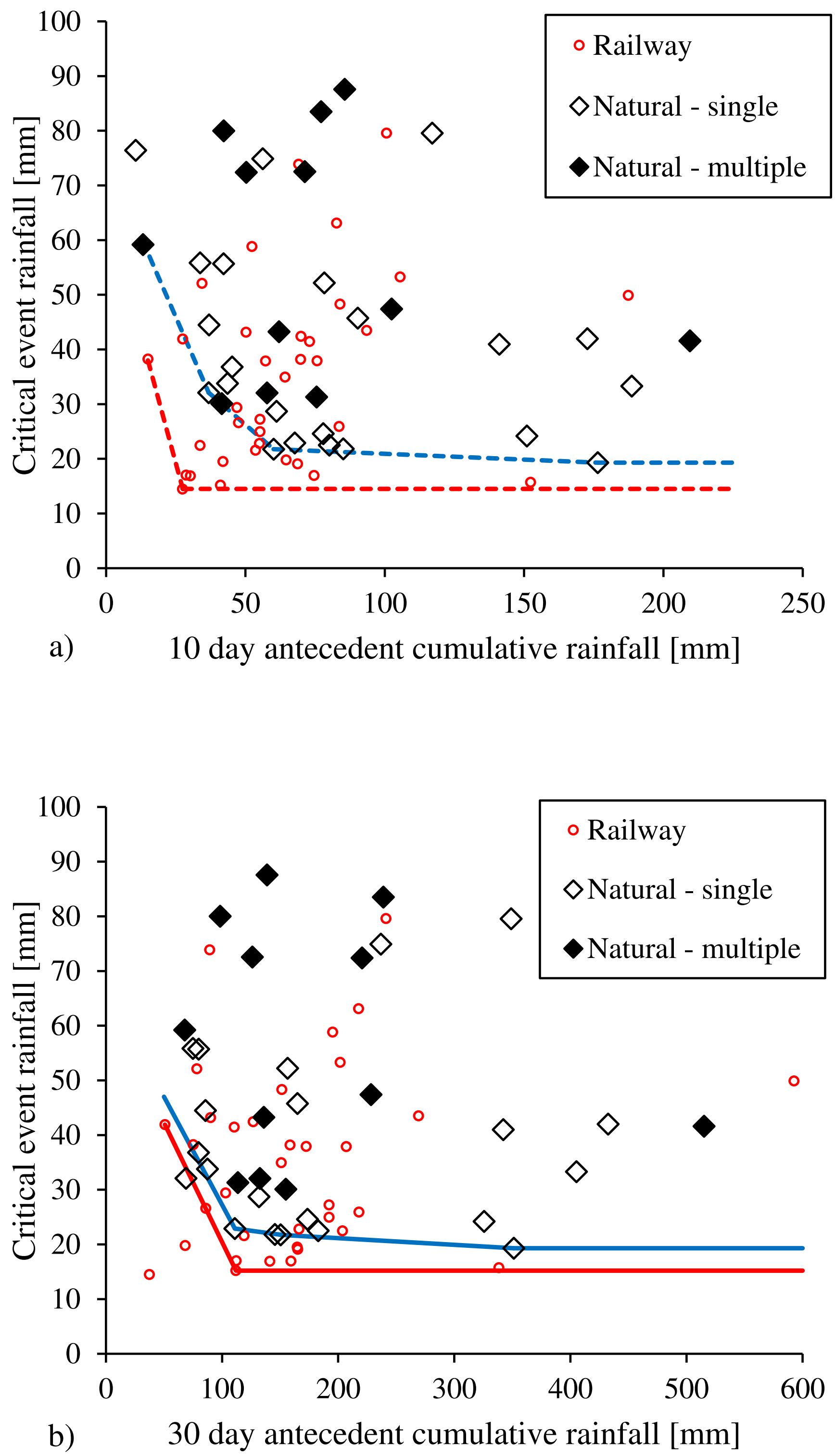

Fig. 8. Cumulative – antecedent rainfall thresholds for landslides on rail network (red line) and landslides on natural terrain (blue line): a) 10 day antecedent period and b) 30 day antecedent period. Landslide events on rail network in red circles. Landslide events on natural terrain in black diamonds. Empty diamond – single landslide event, full diamond – multiple (widespread) landslide event.

shrinkage of the material during a dry period, causing cracking and opening preferential infiltration channels to critical depths (Long and Jennings, 2006; Reale et al., 2012); and partly by the dearth of available data.

While the extent/accuracy of this study is limited due to relatively small amount of data available and the simple graphical method of analysis adopted, the preliminary results show some clear patterns. In general, both I-D and critical-antecedent rainfall thresholds suggest a clear difference in rainfall characteristics that trigger landslides on railway earthworks and natural terrain slopes, with rainfall thresholds being higher for natural slopes. This can be attributed to two principal reasons: glacial action and the condition of the rail network. As a result of the last glacial period of 12,000 years ago, most of natural hillslope surfaces in Ireland exhibit either a thin layer of glacially derived

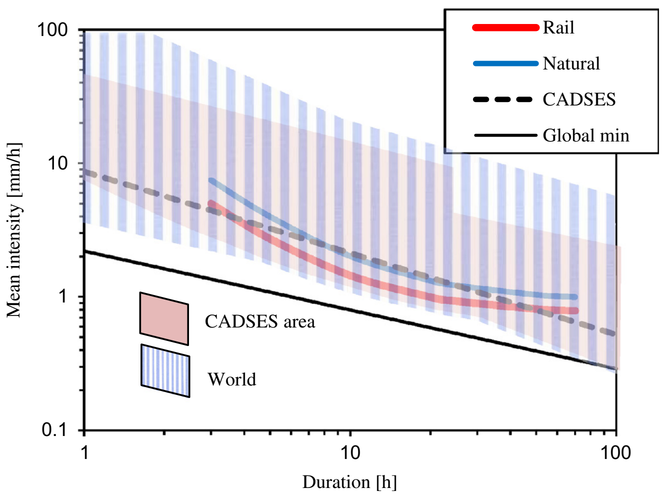

Fig. 9. Range of thresholds collated by Guzzetti et al. (2007) in a) CADSES area (red) and b) world (striped blue). Thresholds for rail earthworks (red line, thicker) and natural slopes (blue line, thinner); thresholds for CADSES area (Guzzetti et al., 2007, dashed black line) and global threshold (thin black line Guzzetti et al., 2008) superimposed.

colluvium or outcropping bedrock. Slopes with significant depths of soil or weathered rock are rare, thus limiting the potential for landslides. Martinović et al. (2016a) showed that Irish Rail earthworks that were constructed in the 1800's before the development of soil mechanics theories are far steeper than those constructed using modern standards. When combined with mechanical degradation this causes them to fail when subjected to much lower rainfall events than natural slopes.

5. Comparison with existing thresholds

The rainfall thresholds developed for landslides on rail earthworks and natural slopes in this study represent national thresholds since they are based on events that were recorded over the entire country of Ireland. However in topographical terms they should be considered as regional thresholds, given the size of the study area and the similarity of climatic and physiographic characteristics within it. This allows them to be compared to I-D thresholds proposed elsewhere in Europe and indeed worldwide. In Fig. 9 the Irish I-D thresholds are compared with 52 I-D thresholds collated by Guzzetti et al. (2007). These thresholds include global, regional and local thresholds from all over the world. Thresholds representing the CADSES area (Central European Adriatic Danube South-Eastern Space, essentially covering entire Central and South-Eastern Europe) were highlighted. The asymptotic nature of Irish threshold curves makes comparison less straightforward, especially for very short (<5 h) and very long (>50) rainfall durations. However, as 50 of the 56 landslide events (89.3%) used in this study have durations of between 5 and 50 h, this segment can be successfully compared to the collated thresholds. The Irish thresholds for engineered and natural slopes are shown to be at the very bottom of both ranges, indicating that landslides in Ireland can be triggered by rainfall intensities lower than in most other parts of Europe and the world. Furthermore, the threshold for landslides on natural slopes in Ireland corresponds well to those developed by Guzzetti et al. (2007) for the CADSES area and the sub-part developed for severe mid-altitude climate. The threshold for Ireland is located above the minimum global threshold developed by Guzzetti et al. (2008).

The thresholds shown in Fig. 9 were developed for vastly different climatological and physiographical areas, which in part explain the large variation in intensity levels. To enable a more meaningful comparison, thresholds can be normalised by an appropriate characteristic of local climate. One of more common normalisation approaches is to divide the rainfall intensity with the mean annual precipitation (MAP) (Saito et al., 2010; Zhou and Tang, 2014; Guo et al., 2016). Following this, pairs of values for landslides on rail earthworks in Ireland from I-D threshold (Fig. 5) were re-plotted in I_{MAP}-D graph (Fig. 10). An added benefit of this approach is that it allows one to normalise the events internally within the study region by taking account of differences in MAP throughout Ireland, which generally decrease from the West to the East coast of Ireland. The I_{MAP}-D pairs of values show a very tight grouping and a clear descending trend, indicating very high precision and usefulness of I_{MAP}-D data. A power law I_{MAP}-D threshold was then determined, see Eq. (5).

$$I_{MAP} = 0.015 \times D^{-0.89} \ (1 < D < 100) \tag{5}$$

On the same figure, the I_{MAP}-D threshold was superimposed with 19 I_{MAP}-D thresholds collated by Guzzetti et al. (2007), shown as the shaded area. The threshold for landslides on the Irish Rail network falls below the shaded range, indicating that rainfall sufficient enough to trigger landslides in Ireland is weak in both absolute and relative terms. The Irish threshold is still located above the minimum global threshold developed by Guzzetti et al. (2008).

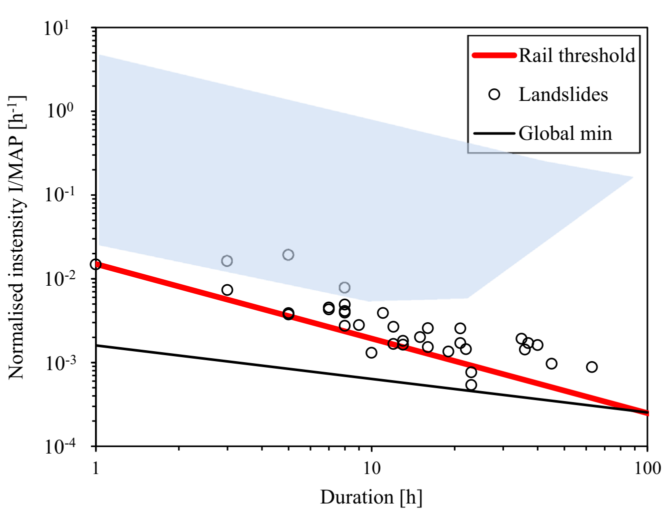

Fig. 10. I_{MAP}-D threshold for landslides on rail earthworks in Ireland. Shaded area – extent of I_{MAP}-D thresholds collated by Guzzetti et al. (2007). Global minimum I_{MAP}-D threshold – thin black line (Guzzetti et al., 2008).

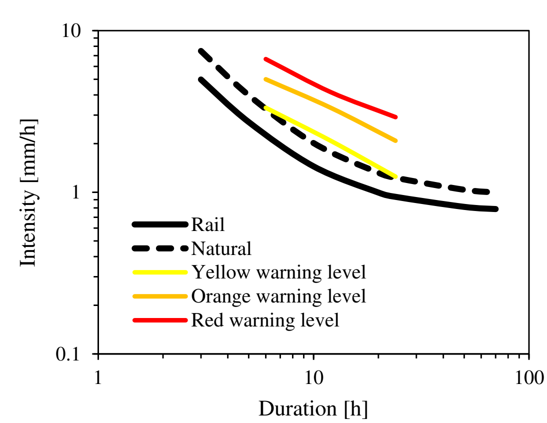

Fig. 11. I-D thresholds for landslides in Ireland and Met.ie rainfall warning levels.

6. Applicability of rainfall thresholds for Early Warning Systems

Landslide rainfall thresholds represent a useful tool in predicting the frequency of triggering occurrences, and could consequently play a valuable role in landslide risk mitigation. Different rainfall thresholds are used to determine the limits of Early Warning Systems (EWS) developed for various areas and used by local or regional authorities worldwide (Aleotti, 2004; Baum and Godt, 2010; Huang et al., 2015; Piciullo et al., 2016). While Ireland does not have an EWS dedicated specifically to landslides, The Irish Meteorological Service holds a general weather warnings system (Met Éireann, 2016). Warnings are not hazard-specific, i.e. they are not developed for the particular hazards such as landslides or floods. Instead they provide warning levels for a range of general hazard sources such as rainfall, wind, extreme temperatures etc. Rainfall warning levels are classified as either yellow, orange or red warning depending on severity with yellow being the least severe and red the most. The criteria for each of them are expressed in cumulative event rainfalls for a set of durations that range between six and 24 h, enabling the authors to build I-D curves for each warning level. These warning levels are plotted in Fig. 11 alongside the I-D thresholds developed in this study. Inspection of the figure reveals that landslides on both natural and engineered slopes can already be expected at the yellow warning level. Orange and red warning levels are situated considerably above the landslide threshold, which is some cause for concern. An obvious implication of this analysis is that rainfall related landslides may feasibly occur without any weather alert being raised. This has serious repercussions for infrastructure operators like Irish Rail who might depend on weather alerts for safe management of operations (i.e. reducing speed etc.). The need for a railway earthworks–specific warning system is evident in this case. The same logic can be applied to all infrastructure operators worldwide that use landslide thresholds developed for natural slopes or generalised weather warning levels.

To assess the number of landslide-triggering rainfall events in Ireland, a recurrence period of rainfall events which exceed the rainfall thresholds can be determined. This can be carried out either by directly counting the events within a certain time period (Jaiswal and van Westen, 2009) or by comparing the threshold with existing intensity-duration-frequency (IDF) curves developed on the basis of a statistical assessment of historical precipitation data series. The Irish Meteorological Service provides depth-duration-frequency tables for a wide range of durations and frequencies over a grid of areas in Ireland. Comparing the rail threshold with the IDF curves does not yield a unique answer due to the asymptotic nature of the threshold and the variation of rainfall frequencies throughout the study area. However, the range of recurrence periods for the most common rainfall durations (between 5 and 30 h) can be determined. It spans from as low as 0.17 on the Western coast to 0.33 in the Dublin region of eastern coast, translating to approximately four to six landslide-triggering rainfall events per year.

In reality, not every exceedance of threshold will result in a landslide, because slope stability largely depends on factors other than rainfall, such as the topographical, geotechnical, morphological and saturation characteristics of the slopes in question (Aleotti and Chowdhury, 1999). This is especially visible at rail earthwork slopes in Ireland, where a significant number are stable despite being built >150 years ago (Reale et al., 2016), while some have suffered multiple failures. In finding the frequency of landslide events, some researchers also consider the conditional probability of occurrence of a landslide given that the threshold has been exceeded, $P\{L|R > R_T\}$ (Jaiswal and van Westen, 2009; Berti et al., 2012). The value of this conditional probability for rail threshold developed in this study is low due to the selection of the minimum threshold, resulting in relatively large frequency of rainfall events surpassing the threshold. A more complete dataset of those rainfall events that caused the landslides and those that did not trigger the failure is needed to quantify this probability. Using this data it would also be possible to develop a family of complementing thresholds, each pertaining to a specific value of $P\{L|R > R_T\}$, effectively developing a tailor-made early warning system for a particular transport network.

7. Conclusions

A database of 35 landslides that occurred on engineered slopes located on the Irish railway network was collated and the relevant precipitation data at the time of slope failure was interrogated to develop a suite of rainfall thresholds. The derived intensity-duration (I-D) thresholds and in particular normalised intensity-duration (I_{MAP}-D) thresholds were shown to be very consistent and suitable for the development of threshold levels. For thresholds considering antecedent rainfall, it was observed that the mid-term 10 days antecedent rainfall exhibits a stronger relation with critical event rainfall than the longer term 30 day antecedent rainfall.

The study compared rainfall thresholds developed for engineered slopes to thresholds for natural slopes at a national scale. For that purpose, data on 34 landslides which occurred on natural slopes in Ireland was compiled along with the associated precipitation records. These were used to develop both I-D and critical – antecedent rainfall thresholds for natural slopes in Ireland. Comparing these to thresholds developed for engineered slopes showed that while I-D thresholds observe very similar shape and exhibit relatively small differences in required intensities, over a third of earthwork failures were located below the natural terrain threshold, proving that thresholds developed for natural terrain should not be applied to engineered slopes. Furthermore, more intense rain combined with increased antecedent rainfall was found to be needed to trigger landslides on natural slopes. As a result engineered slopes are more vulnerable to rainfall induced slope failures and more conservative warning limits may be appropriate. Unfortunately this has serious implications for infrastructure managers using rainfall thresholds not specifically developed for engineered slopes, even if the thresholds in question are from the same catchment area. The two sets of thresholds were then further compared to existing thresholds published in Europe and worldwide. The comparison revealed that in an Irish context a relatively low intensity rainfall can be a triggering event, even when thresholds were normalised to disregard the effect of local climates. This is likely due to the high soil moisture naturally present in Irish soils as a combined result of the low evaporation rates and the large number of rainy days. The differences between the thresholds confirm the known limits of rainfall threshold application, namely their inability to predict outside of its study area or outside of the landslide or asset types, which they were developed for.

Finally, rainfall thresholds were compared to a general weather warning system currently used by Met Éireann in Ireland. The rainfall threshold developed for the rail network was shown to be significantly more conservative than the lowest weather warning alert. This indicates that there is a significant risk involved when using general weather alerts for infrastructure management, and showcases the need for developing railway specific rainfall thresholds for landslides. The same logic might be applied to all aging transport infrastructure networks across Europe who are currently dependent on non-network-specific warning systems. It should be noted however that due to the limited number of landslide events in this study, non-consideration of rainfall events not associated with landslide events and the reduced time period (2008–2016), these conclusions cannot be readily generalised worldwide and require further research to confirm the applicability for other study areas.

While the preliminary results of this study are limited by the dearth of data available, the simple graphical method of determining the thresholds adopted and inherent limitations of rainfall threshold methodology, the approach demonstrates the usefulness of developing rainfall thresholds for assessing the temporal aspect of landslide hazard on a regional scale for transport network earthworks.

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