OPEN ACCESS Freely available online

Journal of Geology & Geophysics

ISSN: 2381-8719

Research Article

Landsliding in the UK: A Statistical Analysis of Long-Term Trends in Intense Rainfall Events

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ABSTRACT

Intense rainfall events are known to be important controls on landslide activity in the UK. This paper presents an analysis of daily rainfall records from 56 stations throughout the UK involving the application of a non-parametric statistical test to evaluate the significance of any trends in these time series. Four intense rainfall scenarios are considered: >25 mm/day; >40 mm over 2 days; >60 mm over 3 days and >80 mm over 7 days. The results indicate that there is significant spatial variation in the long-term trends. A positive trend of increasing intense rainfall event frequency is not present across the UK except at some upland stations in the Scottish Highlands and Southern Uplands, and the Northern Pennines.

Keywords: Landslide; Rainfall; Hypotheses

INTRODUCTION

"There are many definitions of 'trend', but none apply to differences that have already been found to be non-significant in a statistical test [1]."

The evaluation of trends in climatic time series is an important factor for risk assessment and the long-term design of services and infrastructure. This is so in the UK where rainfall is a common trigger for landslide activity [2-5]. Reactivation of pre-existing deep-seated landslides is generally associated with prolonged heavy rainfall. Shallow translational (debris) slides, peat slides and debris flows in steep catchments are often associated with high intensity rainstorms. Such landslides tend to be triggered within minutes or hours of the event, although the antecedent rainfall prior to the landslide event can also be significant.

Rainfall generates landslides by infiltrating into the slope while increasing positive pore-water pressures within the material above the potential surface of rupture to a critical level. The infiltration rate is influenced by factors such as the slope angle, the vegetation cover, surface stoniness, and the permeability of the slope materials. On the other hand, resistance of the slope depends on soil or rock strength and on its geometry. As a result, the critical rainfall necessary to cause the slope failure will vary from one slope to another, and one environment to another [6].

Although many attempts have been made to determine the minimum rainfall required for causing slope failures (see the discussions in Corominas et al. [6], and Winter et al. [7]) few have focussed on conditions in the UK. Pennington et al. [8], demonstrated that a marked increase in the number of reported landslides in SW England and Wales during the very wet period between November 2012 and January 2013 was closely correlated with the antecedent precipitation over 1-7 day periods. The threshold rainfall levels associated with the triggering of 6 or more landslides in the region were around 25 mm in 1 day and around 100 mm in 7 days.

In the Scottish Highlands, Winter et al. [8], developed a deterministic rainfall threshold for debris flow potential, based on 16 past events that had caused disruption to the road network and for which information on the timing and rainfall intensities was known (Figure 1). Rainfall events that plot above the threshold line triggered landslides. The time limit of antecedent rainfall duration was considered to be 288 hours (45 mm of rain over 12 days). Probabilistic thresholds were subsequently developed [9], primarily for the area around the A83 Rest and be Thankful [10,11].

This paper presents an analysis of long-term daily rainfall records from stations throughout the UK and applies a non-parametric statistical test to evaluate the significance of any trends in these time series. In doing so, the objectives are to establish whether one of the major controls on landslide activity in the UK has changed significantly over the last century or more, and whether there is a consistent pattern across the UK as a whole.

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Received: 02-Apr-2023; Manuscript No. JGG-23-22805; **Editor assigned:** 04-Apr-2023; PreQC. No. JGG-23-22805 (PQ); **Reviewed:** 18-Apr-2023; QC. No. JGG-23-22805; **Revised:** 25-Apr-2023; Manuscript No. JGG-23-22805 (R); **Published:** 02-May-2023, DOI: 10.35248/2381-8719.23.12.1094.

Citation: Lee EM (2023) Landsliding in the UK: A Statistical Analysis of Long-Term Trends in Intense Rainfall Events. J Geol Geophys. 12:1094.

MATERIALS AND METHODS

Intense rainfall events in the UK

By comparison with global maxima, the UK experiences relatively low intensity rainfall (Figures 1 and 2; the highest daily rainfall in the UK, 297 mm is around 15% of the world record value of 1825 mm recorded at Foc Foc, Réunion Island in the Indian Ocean). However, a daily rainfall of 100 mm of more has been surpassed in many parts of the country [12]. These extreme events can be associated with a variety of weather conditions, including summer convective storms, prolonged frontal (widespread) or winter orographically forced events [13].

The 1 in 100 year return period 24-hour rainfall total varies with the average annual rainfall [13]:

- Annual rainfall >2800 mm: 228 mm (high ground in the Scottish Western Highlands, parts of the Lake District and Snowdonia).
- Annual rainfall 1400-2800 mm: 152 mm (parts of the Scottish Highlands, high ground in the Southern Uplands, the Lake District and the Pennines, mid Wales, the Mendips, Exmoor and Dartmoor, and high ground in Northern Ireland).
- Annual rainfall 500-1400 mm: 100 mm (the rest of the UK, notably eastern Scotland and much of eastern, central and southern England).

Although the largest multiple-day totals occur in upland areas (Table 1a), most of the heaviest daily falls recorded have occurred in lowland UK [13], most notably in south west England (Table 1b):

Table 1a: UK rainfall records: Highest 2 to 4 day and 1 monthly totals.

Days	Rainfall (mm)	Date	Location
Highest 2-day total	405	4 to 5 December 2015	Thirlmere (Cumbria)
Highest 3-day total	456.4	17 to 19 November 2009	Seathwaite (Cumbria)
Highest 4-day total	495	16 to 19 November 2009	Seathwaite (Cumbria)
Highest monthly total	1396.4	1 to 31 December 2015	Crib Goch (Snowdon)

Table 1b: UK rainfall records: Highest daily totals.

Country	Rainfall (mm)	Date	Location
England*	279	18-Jul-1955	Martinstown (Dorset)
Northern Ireland	159	31-Oct-1968	Tollymore Forest (County Down)
Scotland	238	17-Jan-1974	Sloy Main Adit (Argyll and Bute)
Wales	211	11-Nov-1929	Lluest Wen Reservoir (Mid Glamorgan)

Note: * The highest 24-hour total for any 24-hour period is 341.4 mm from 18:00 GMT on 4th to 18:00 GMT on 5th December 2015 at Honister Pass (Cumbria).

These daily totals disguise the intensity of the extreme short duration storms that have been reported (Table 1c). For example, during the Hampstead storm of 14 August 1975 169 mm fell in 155 minutes. Such intense storms generally affect only small areas, although the resultant flash floods can have a devastating impact in small, steep catchments, (e.g. the Lynmouth floods of 15th August 1952, Bleasedale et al. [14]; the Boscastle flood of 16th August 2004, Golding et al. [15]).

Table 1c: UK rainfall records: Highest short duration totals.

Minutes	Rainfall (mm)	Date	Location
Highest 5-minute total	32	10 August 1893	Preston (Lancashire)
Highest 30-minute total	80	26-Jun-1953	Eskdalemuir (Dumfriesshire)
Highest 60-minute total	92	12-Jul-1901	Maidenhead (Berkshire)
Highest 90-minute total	117	08-Aug-1967	Dunsop Valley (Lancashire)
Highest 120-minute total	155	11-Jun-1956	Hewenden Reservoir (West Yorkshire)
Highest 155-minute total	169	14-Aug-1975	Hampstead (Greater London)
Highest 180-minute total	178	07-Oct-1960	Horncastle (Lincolnshire)

- Martintown, Dorset; 297.4 mm on 18 July 1955.
- Bruton, Somerset; 242.8 mm on 28 June 1917.
- Cannington, Somerset; 238.8 mm on 18 August 1924.
- Lynmouth, Devon; 229 mm on 15 and 16 August 1952.

Rodda et al. [12], suggested that site specific events of this nature may have had a return period of many thousands of years.

Intense rainfall scenarios

The intense rainfall scenarios used in this analysis are:

Scenario 1: >25 mm in 1 day (the equivalent of 1.04 mm/hour for 24 hours).

Scenario 2: >40 mm in 2 days (the equivalent of 0.83 mm/hour for 48 hours).

Scenario 3: >60 mm in 3 days (the equivalent of 0.83 mm/hour for 72 hours).

Scenario 4: >80 mm in 3 days (the equivalent of 0.47 mm/hour for 168 hours).

All 4 scenarios plot above the deterministic debris flow triggering threshold line developed by Winter et al. [9], for Scotland (Figure 1). However, this should not be taken as implying that the triggering threshold has universal applicability or that the occurrence of any of the scenarios would necessarily lead to shallow landsliding everywhere across the UK. The scenarios have been adopted simply as convenient measures of rainfall intensity as potential landslide triggers.

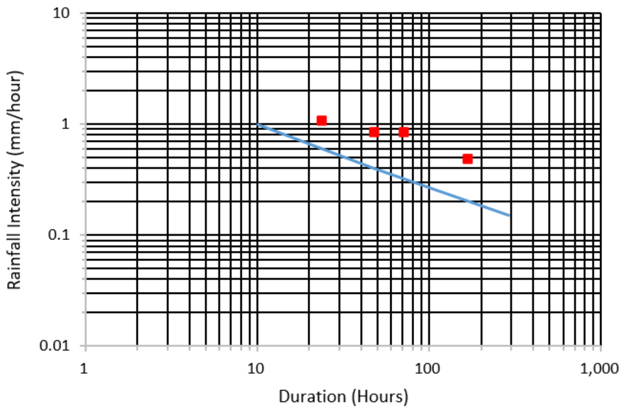

Figure 1: Debris flow triggering threshold: Plot of rainfall intensity (mm/hour) and duration (modified, after Winter et al 2019). Note that the 2 extremes of the original threshold (prior to 10 hours and after 12 days) have been removed, as suggested by Winter (2020). **Note:** ( ) Trigger threshold, ( )intense rainfall scenario.

UK historic station data

Daily rainfall records for a variety of UK weather stations is available from the Koninklijk Nederlands Meteorologisch Instituut (KNMI) Climate Explorer website: https://climexp.knmi.nl/selectdailyseries.cgi?id=someone@somewhere

Records were accessed from this site for stations with over 50 years of daily data. A total of 56 stations were selected (Table 2), of which 9 sites had data for over 100 years (the longest records are for Oxford with 192 years of data and Armagh, Northern Ireland, with 180 years of data). Note that "rain days" are from 09:00 GMT to 09:00 GMT the next day.

Most of the time series include a small number of missing daily values for rainfall. These have been infilled by taking the average of the previous and following days; thus, if the missing data value was for 10 January 2000, the infilled value would be the average of the values for 9 and 11 January 2000.

A summary of the data is presented in Table 3 and Figure 3 which reveals marked contrasts across the UK. In very broad terms, three groups of stations can be identified on the basis of the frequency of events >25 mm/day:

1. Group 1 with very frequent high intensity rainfall events (e.g. on average, >10 daily rainfall events >25 mm, per year): Benmore, Eskdalemuir, Glenlee, Kilnochewe and Leadhills. These stations occur in the Western Highlands and Southern Uplands of Scotland.

2. Group 2 with frequent high intensity rainfall events (e.g. on average, 5-10 daily rainfall events >25 mm, per year): Alwen (Snowdonia, North Wales), Malham Tarn and Kielder (Northern Pennines, England), Bute Rothesay, Ardtalnaig (Highlands, Scotland) and Threave (Southern Uplands, Scotland).

3. Group 3 with relatively infrequent high intensity rainfall events (e.g. on average, <5 daily rainfall events >25 mm, per year): The remaining 46 sites which typically occur in lowland and eastern UK.

Elevation, latitude and west to east rain-shadow effects have important influences on these groupings, but the patterns are complex (Figure 4; see Hulme et al. [16], for a detailed discussion about the variation in precipitation across the UK). The stations with the most extreme rainfall climate include Benmore (Scenario 1: On average 23.1 events/year; Scenario 2: On average 28.4 events/year; Scenario 3: On average 22.4 events/year; Scenario 4: On average 71 events/year), Kilnochewe (Scenario 1: 18.5 events/year; Scenario 2: 24.3 events/year; Scenario 3: 20.3 events/year; Scenario 4: on average 57 events/year), both of which are in the Western Highlands.

Intense rainfall frequency

For each station a count was made of the number of times the intense rainfall scenarios occurred per year over the available record. Figures 5 and 6 present the time series for Oxford (England) and Eskdalemuir (southern Scotland) as examples.

The non-parametric Mann-Kendall (MK) test [17,18], has been used to assess if there is a monotonic upward or downward trend (i.e. not cyclic or stepped) of the frequency of intense rainfall events over time, and whether the trend is statistically significant or not.

Table 3: Stations used in this analysis: Basic statistics.

Station	LAT	LONG	Elevation (m)	Record		Record (Years)	Mean annual rainfall (mm)
				Start	End		
Aberporth	52.14	-4.57	133	1960	2018	59	883
Alice Holt Lodge	51.18	0.85	115	1962	2017	56	782
Alwen	53.06	-3.55	345	1961	2017	57	1263
Ardtalnaig	56.53	-4.11	130	1961	2017	57	1343
Armagh	54.35	-6.65	62	1838	2019	180	812
Auchincruive	55.48	-4.57	48	1961	2017	57	978
Benmore	56.03	-4.99	12	1961	2017	57	991
Bognor Regis	50.78	0.68	7	1960	2017	58	795
Bowhill	55.54	-2.90	168	1961	2017	57	1521
Bradford	53.81	-1.77	134	1960	2017	58	857
Bude	50.83	-4.55	15	1960	2017	58	932

Bute Rothesay	55.84	-5.06	43	1961	2012	52	1471
Durham	54.77	-1.59	102	1880	2017	138	641
Dyce	57.21	-2.20	65	1960	2017	58	814
East Bergholt	51.96	1.03	7	1961	2017	57	569
Eastbourne	50.76	0.29	7	1911	2016	106	794
Edinburgh	55.97	-3.21	26	1961	2017	57	715
Eskdalemuir	55.31	-3.21	242	1931	2017	87	1742
Glenlee	55.10	-4.19	55	1961	2012	52	1638
Hastings	50.85	0.57	45	1961	2017	57	731
Hawarden Bridge	53.22	-3.03	5	1951	2004	54	617
Hayling Island	50.78	0.98	4	1961	2016	56	703
Heathrow	51.48	-0.45	25	1960	2018	59	754
High Mowthorpe	54.10	0.64	175	1961	2017	57	729
Hull	53.77	0.37	2	1931	1999	69	664
Hurn	50.78	-1.84	10	1960	2018	59	789
Inverness	57.49	-4.22	4	1961	2012	52	740
Keele	53.00	-2.27	179	1961	2017	57	806
Kielder Castle	55.23	-2.58	201	1961	2017	57	999
Kilnochewe	57.61	-5.31	25	1961	2017	57	2282
Leadhills	55.42	-3.76	393	1961	2017	57	1742
Leckford	51.12	-1.44	117	1961	2012	52	779
Lerwick	60.14	-1.18	82	1946	2018	73	1257
Leuchars	56.38	-2.86	10	1960	2018	59	690
Lyneham	51.50	-1.99	145	1960	2017	58	745
Lyonshall	52.21	-2.97	155	1961	2013	53	793
Malham Tarn	54.10	-2.16	381	1961	2017	57	1550
Malvern	52.11	-2.31	62	1900	2008	109	738
Morpeth	55.22	-1.69	95	1960	2017	58	693
Newton Rigg	54.67	-2.79	169	1906	2017	112	867
Nottingham	53.01	-1.25	117	1960	2017	58	709
Oxford	51.76	-1.26	63	1827	2018	192	660
Paisley	55.85	-4.43	32	1914	2010	97	1245
Penicuik	55.82	-3.23	185	1961	2017	57	982
Plymouth	50.35	-4.12	50	1960	2017	58	1007
Ronaldsway	54.08	-4.63	16	1960	2017	58	864
Rothamsted	51.81	0.36	128	1916	2017	102	712
Sheffield	53.38	-1.49	131	1883	2017	135	835
Slapton	50.29	-3.65	32	1961	2017	57	1074
Stormont	54.06	-5.83	56	1961	2017	57	861
Stornoway	58.21	-6.32	9	1931	2017	87	1249
Threave	54.92	-3.95	73	1961	2017	57	1142
Tiree	56.50	-6.88	9	1960	2017	58	1255
Waddington	53.18	-0.52	68	1949	2018	70	614
Wick	58.45	-3.09	36	1931	2018	88	814
Wisley	51.31	0.47	38	1908	2017	110	656

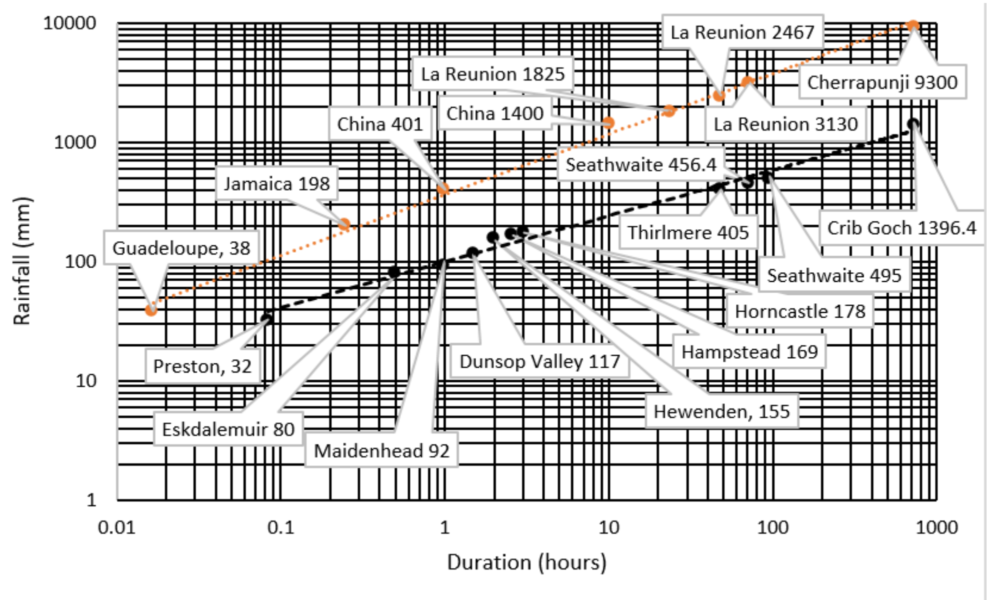

Figure 2: Magnitude-duration relationships for the World (top line) and UK (bottom line) record rainfall events.

Table 2: Stations used in this analysis: Basic statistics.

Station	Events/Year Daily Rainfall (>25mm)			Events/Year 2 Day Rainfall (>40mm)			Events/Year 3 Day Rainfall (>60mm)			Events/Year 7 Day Rainfall (>80mm)		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean
Aberporth	0	6	2.1	0.0	4.0	1.4	0	4	0.4	0	9	1.4
Alice Holt Lodge	0	6	2.5	0.0	7.0	1.8	0	5	0.7	0	12	1.9
Alwen	1	10	5.7	0.0	15.0	6.6	0	13	3.1	0	6	0.6
Ardtalnaig	0	13	6.6	0.0	16.0	6.9	0	15	4.4	0	47	15.8
Armagh	0	8	1.6	0.0	6.0	0.9	0	4	0.3	0	11	0.6
Auchincruive	0	7	1.9	0.0	8.0	1.2	0	10	0.7	0	28	8.7
Benmore	11	42	23.1	12.0	46.0	28.4	6	48	22.4	27	128	70.8
Bognor Regis	1	10	2.3	0.0	7.0	1.2	0	3	0.3	0	10	1.2
Bowhill	0	7	2.3	0.0	7.0	2.0	0	5	1.0	0	12	2.4
Bradford	0	6	2.3	0.0	7.0	1.9	0	5	0.9	0	14	1.8
Bude	0	7	1.8	0.0	8.0	1.2	0	5	0.5	0	9	1.3
Bute Rothesay	1	12	5.1	0.0	10.0	4.2	0	6	1.5	0	26	9.1
Durham	0	7	1.4	0.0	7.0	1.0	0	5	0.5	0	12	1.0
Dyce	0	7	2.8	0.0	8.0	2.2	0	7	1.1	0	17	2.5
East Bergholt	0	4	1.1	0.0	5.0	0.7	0	3	0.1	0	4	0.2
Eastbourne	0	7	2.4	0.0	6.0	1.9	0	5	0.6	0	14	2
Edinburgh	0	7	1.6	0.0	16.0	5.4	0	5	0.6	0	13	1.2
Eskdalemuir	2	23	10.2	1.0	29.0	29.0	1	25	6.3	0	62	23.8
Glenlee	2	22	11.9	2.0	34.0	12.6	0	19	7.6	3	59	28.0

Hastings	0	8	2.5	0.0	5.0	1.4	0	3	0.5	0	12	1.5
Hawarden Bridge	0	5	1.4	0.0	4.0	0.7	0	3	0.2	0	8	0.5
Hayling Island	0	5	1.7	0.0	7.0	1.2	0	3	0.4	0	9	1.3
Heathrow	0	3	1.4	0.0	6.0	0.8	0	3	0.3	0	6	0.5
High Mowthorpe	0	5	1.7	0.0	6.0	1.6	0	5	0.6	0	13	1.1
Hull	0	6	1.6	0.0	4.0	1.1	0	5	0.4	0	7	0.4
Hurn	0	6	2.7	0.0	9.0	2.1	0	5	0.7	0	11	2.6
Inverness	0	5	1.5	0.0	4.0	1.0	0	4	0.7	0	9	0.9
Keele	0	5	1.5	0.0	5.0	1.0	0	3	0.3	0	5	0.5
Kielder Castle	0	16	6.6	0.0	21.0	5.9	0	16	3.6	0	42	12.4
Kilnochewe	4	37	18.5	2.0	47.0	24.3	1	44	20.3	0	102	57.4
Leadhills	3	23	11.5	10.0	73.0	39.5	0	21	8.1	1	63	30.0
Leckford	0	7	2.3	0.0	6.0	1.6	0	3	0.5	0	12	2.2
Lerwick	0	5	2.1	0.0	7.0	1.5	0	4	0.6	0	15	2.7
Leuchars	0	7	1.9	0.0	6.0	1.4	0	5	0.4	0	7	1.0
Lyneham	0	5	1.4	0.0	4.0	0.8	0	3	0.3	0	7	0.7
Lyonshall	0	7	2.2	0.0	7.0	1.8	0	4	0.7	0	12	1.5
Malham Tarn	1	16	8.6	2.0	19.0	8.7	0	13	4.8	3	39	19.2
Malvern	0	6	2.0	0.0	6.0	1.2	0	3	0.4	0	11	1.1
Morpeth	0	7	2.6	0.0	7.0	1.8	0	7	0.8	0	12	2.0
Newton Rigg	0	7	2.2	0.0	7.0	1.7	0	5	0.6	0	12	1.4
Nottingham	0	4	1.7	0.0	4.0	1.1	0	2	0.3	0	4	0.4
Oxford	0	6	1.4	0.0	6.0	0.8	0	3	0.2	0	7	0.5
Paisley	0	9	4.1	0.0	11.0	3.1	0	7	1.1	0	23	5.3
Penicuik	0	7	2.6	0.0	7.0	2.4	0	6	1.3	0	13	3.1
Plymouth	0	8	3.3	0.0	9.0	1.9	0	10	0.7	0	16	3.1
Ronaldsway	0	7	2.3	0.0	7.0	1.6	0	6	0.6	0	14	1.3
Rothamsted	0	4	1.3	0.0	5.0	0.7	0	6	0.3	0	11	0.7
Sheffield	0	6	2.3	0.0	7.0	1.6	0	6	0.7	0	15	1.7
Slapton	1	10	4.4	0.0	14.0	3.6	0	11	1.5	0	26	6.4
Stormont	0	9	2.7	0.0	10.0	2.1	0	7	1.0	0	12	2.4
Stornoway	0	5	1.7	0.0	6.0	1.1	0	6	0.4	0	14	2.3
Threave	0	12	6.3	0.0	13.0	5.2	0	8	2.1	0	34	8.8
Tiree	0	6	2.1	0.0	7.0	1.6	0	3	0.6	0	19	2.9
Waddington	0	4	1.3	0.0	5.0	0.9	0	3	0.2	0	7	0.4
Wick	0	4	1.1	0.0	4.0	0.6	0	3	0.2	0	7	0.3
Wisley	0	5	1.6	0.0	4.0	1.1	0	3	0.3	0	7	0.7

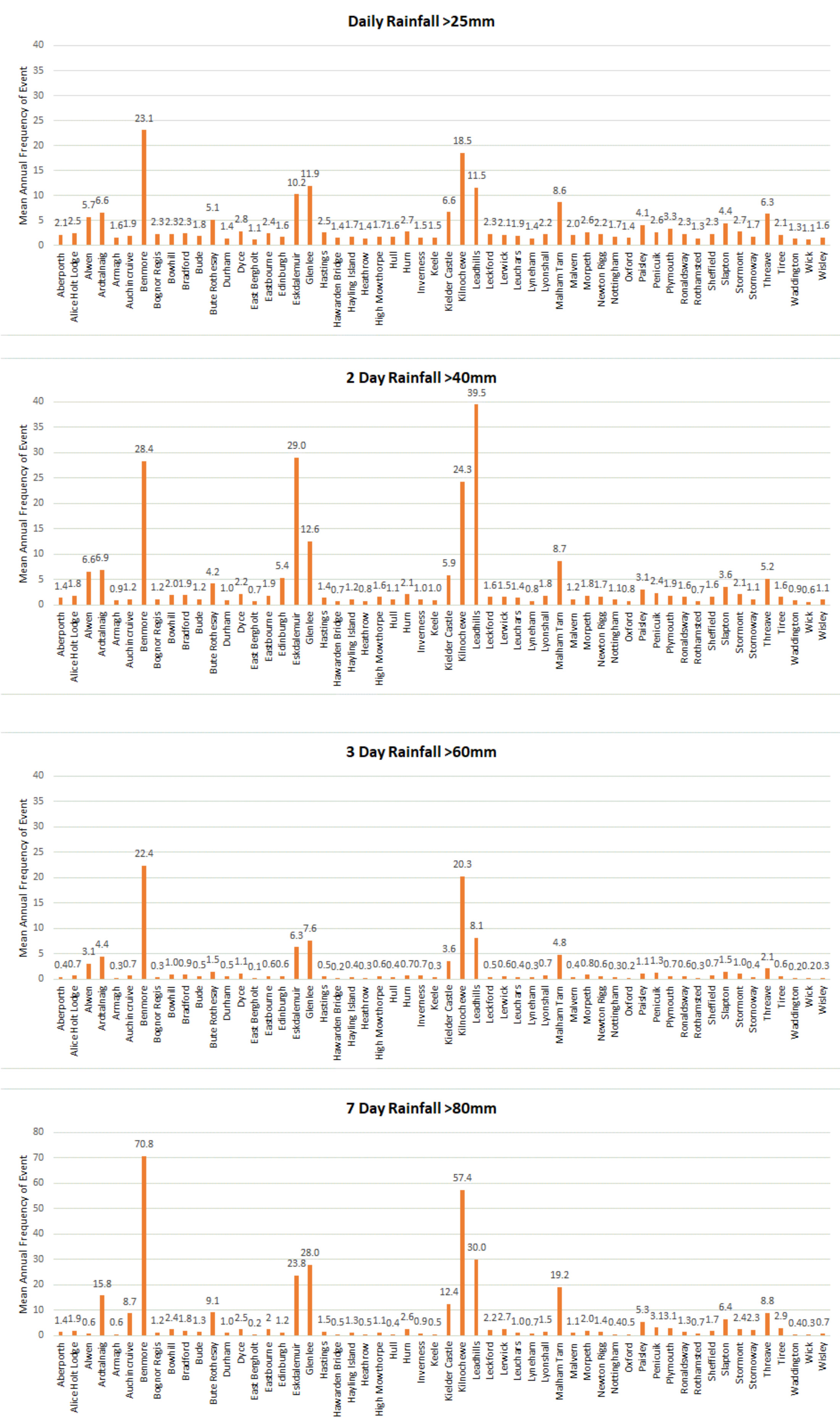

Figure 3: Mean values of intense rainfall scenario frequencies at different stations.

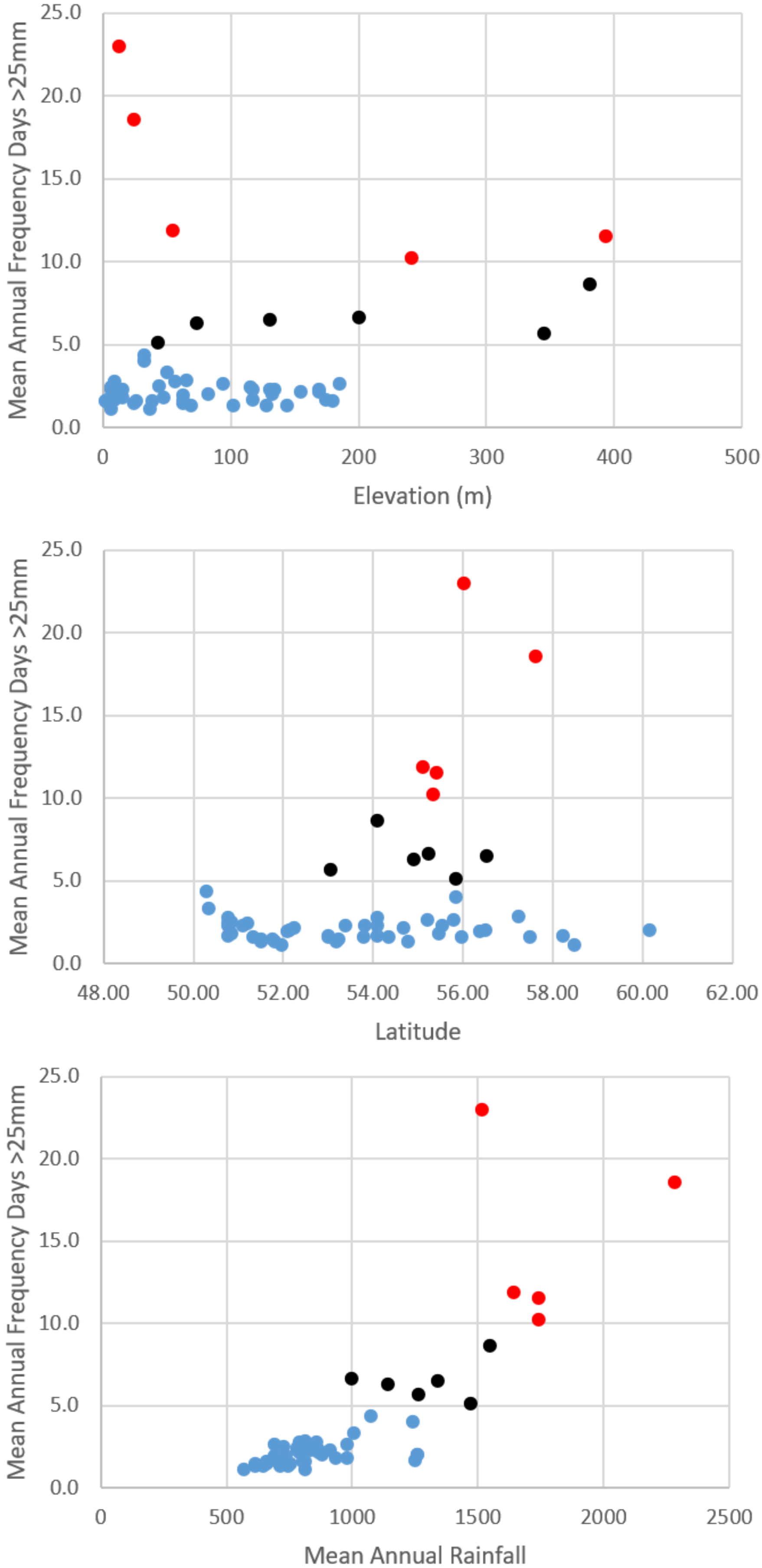

Figure 4: The relationship between intense rainfall events (>25mm/day) and elevation (Top), and latitude (Middle) and mean annual rainfall (Bottom) for the different stations. **Note:** (●) Group 1, (●) Group 2, (●) Group 3.

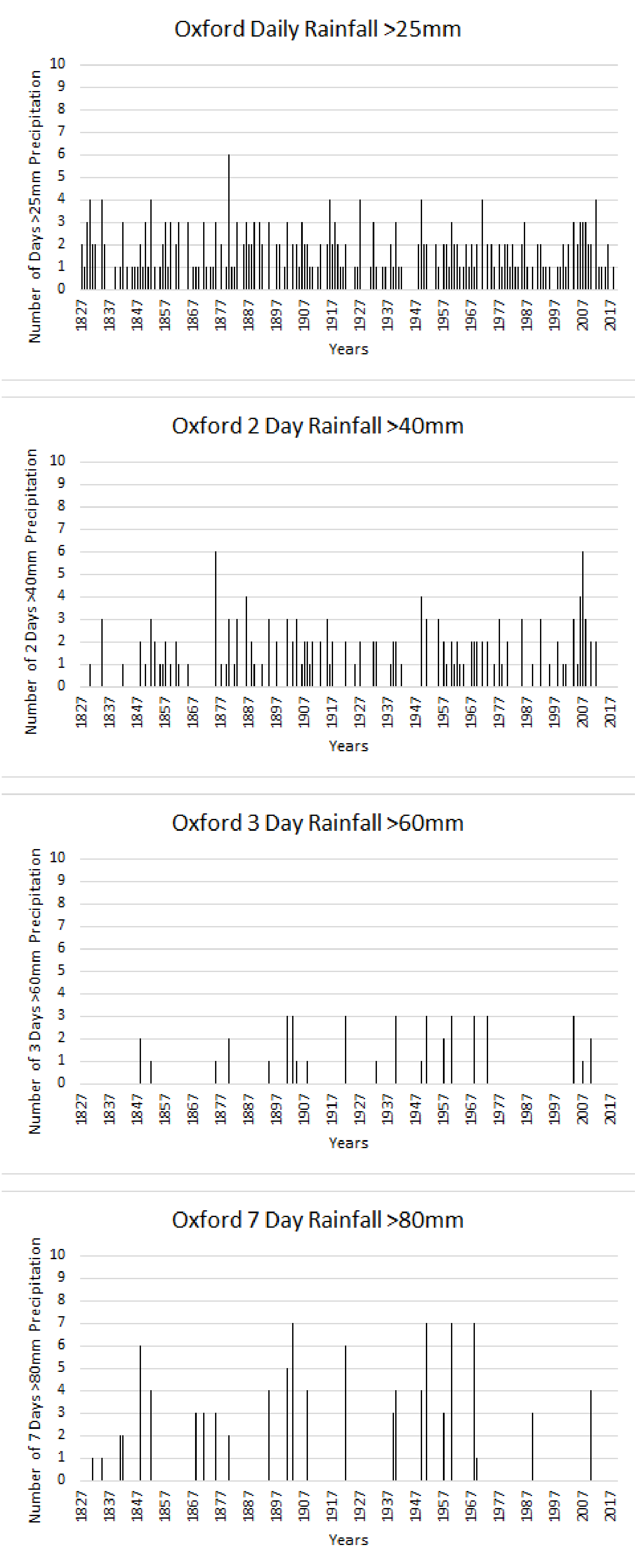

Figure 5: Oxford, England: Frequency of rainfall intensity scenarios (1827 to 2017).

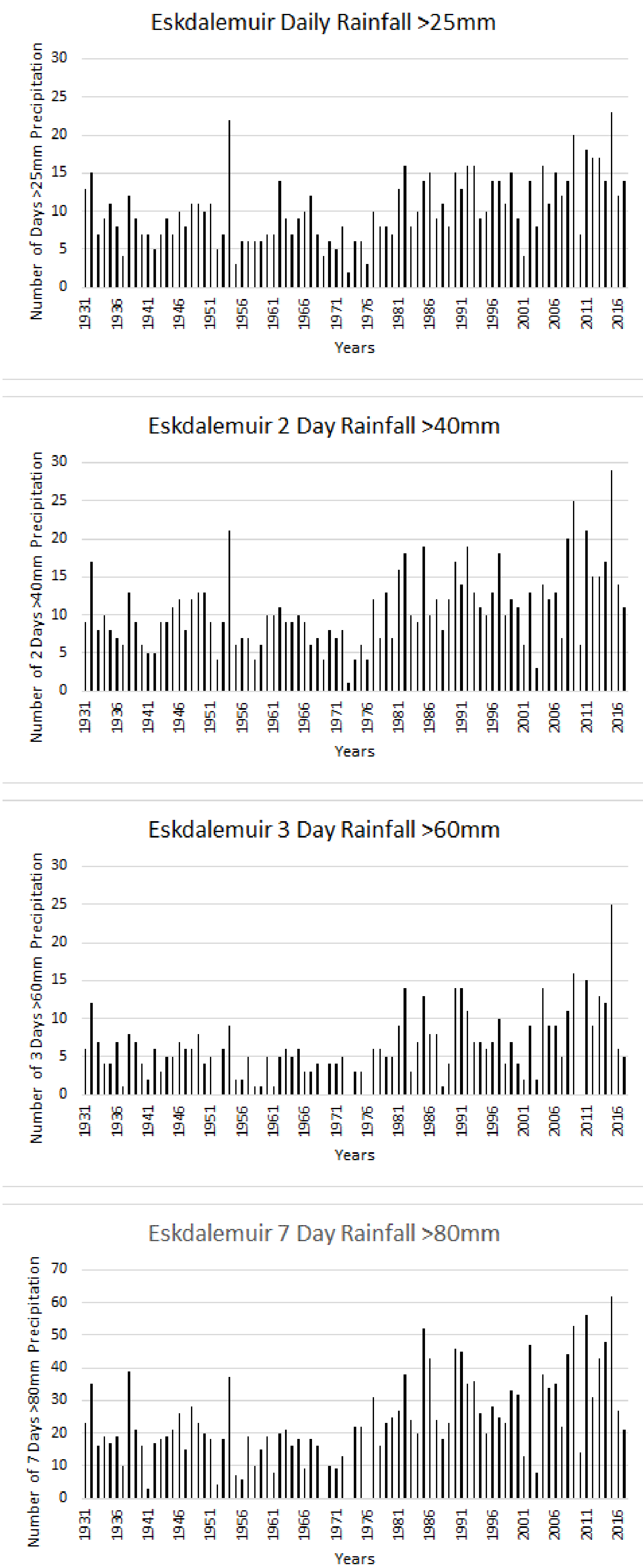

Figure 6: Eskdalemuir, Scotland: Frequency of rainfall intensity scenarios (1931 to 2017).

The Mann-Kendall (MK) test

The MK test analyses the sign of the difference between later-measured data (e.g. an individual annual rainfall total) and earlier-measured data (i.e. from previous years). Each later-measured value is compared to all values measured earlier, resulting in a total of n(n-1)/2 possible pairs of data, where n is the total number of observations (for 100 years of records there will be 4950 pairs for comparison). The test compares the relative magnitudes of the data points rather than the data values themselves [19]. In contrast to linear regression, there is no requirement that the measurements be normally distributed.

The version of the test used in this study was the modification proposed by Hamed et al. [20], which takes account of possible autocorrelation (serial correlation) between the individual records (e.g. Fatichi et al. [21]). The modified MK method tests whether to reject the null hypothesis (H_o; no monotonic trend i.e. the data are independent and randomly ordered) and accept the alternative hypothesis (H_a; monotonic trend is present). The initial assumption is that the null hypothesis (H_o) is true and that the data must be convincing beyond a reasonable doubt before it is rejected and the alternative (H_a) is accepted.

The test S statistic provides an indication of the presence of a trend and whether it is increasing or decreasing; the closer S is to zero the less likely that a trend is present. The null hypothesis is rejected when S is significantly different from zero. When S is a large positive number, later-measured values tend to be larger than earlier values and an upward trend is indicated. When S is a large negative number, later values tend to be smaller than earlier values and a downward trend is indicated. When the value of S is small, no trend is indicated.

It is necessary to compute the Probability (p) associated with S and the sample size to statistically quantify the significance of the trend. The p-value (the "observed significance level") is a measure of the statistical compatibility of the time series data with the null hypothesis (0 for complete incompatibility, 1 for perfect compatibility).

The significance test threshold (alpha) in this analysis has been pre-set at 0.05 significance level. Thus if p<alpha (<0.05 i.e. <5% chance of no monotonic trend) the null hypothesis can be rejected and a statistically significant trend is considered to be present (H_a accepted).

The Sen's slope estimator [22], provides a measure of the slope of the trend; it is considered more accurate than simple linear regression. A positive value indicates an 'upward trend' (increasing values with time), while a negative value indicates a 'downward trend'.

Further details about the Mann-Kendall (MK) test can be found in Lee et al. [23].

RESULTS AND DISCUSSION

The results of the analysis are presented in Table 4 and summarized in Table 5 and Figure 7. The modified MK test (with the alternative hypothesis H_a for any trend, positive or negative) indicates that positive (increasing) trends were found for:

- Group 1 stations in the Western Highlands and Southern Uplands of Scotland (Benmore, Eskdalemuir, Glenlee and Leadhills). Kilnochewe only has a positive trend for the 2 Day>40 mm event.
- Group 2 stations at Malham Tarn and Kielder Castle (Northern Pennines, England), and Ardtalnaig (Highlands, Scotland). However, Alwen (Snowdonia, North Wales), and Threave (Southern Uplands, Scotland) show no positive trends.

Table 4: Modified MK test statistics: Intense rainfall scenarios (alpha=0.05).

Station	Daily Rainfall (>25mm)			2 Day Rainfall (>40mm)			3 Day Rainfall (>60mm)			7 Day Rainfall (>80mm)		
	S statistic	p-value	Trend	S statistic	p-value	Trend	S statistic	p-value	Trend	S statistic	p-value	Trend
Aberporth	-55.0	0.72	No trend	-30	0.74	No trend	33	0.77	No trend	-162.0	0.22	No trend
Alice Holt Lodge	-132.0	0.34	No trend	-145	0.35	No trend	-45	0.76	No trend	-101.0	0.27	No trend
Alwen	100.0	0.47	No trend	70	0.60	No trend	88	0.54	No trend	209.0	0.08	No trend
Ardtalnaig	286.0	0.01	Trend	417	0.00	Trend	404	0.01	Trend	566.0	0.01	Trend
Armagh	-1171.0	0.22	No trend	91	0.90	No trend	462	0.44	No trend	763.0	0.15	No trend
Auchincruive	-21.0	0.89	No trend	53	0.67	No trend	22	0.85	No trend	30.0	0.84	No trend
Benmore	464.0	0.00	Trend	480	0.00	Trend	427	0.00	Trend	452.0	0.00	Trend
Bognor Regis	-105.0	0.54	No trend	-234	0.10	No trend	43	0.74	No trend	-138.0	0.28	No trend
Bowhill	-24.0	0.90	No trend	66	0.54	No trend	191	0.13	No trend	337.0	0.01	Trend
Bradford	13.0	0.90	No trend	-29	0.85	No trend	-54	0.55	No trend	23.0	0.80	No trend
Bude	-53.0	0.72	No trend	-34	0.82	No trend	-86	0.48	No trend	68.0	0.58	No trend
Bute Rothesay	111.0	0.38	No trend	99	0.44	No trend	137	0.26	No trend	297.0	0.00	Trend
Durham	248.0	0.64	No trend	-394	0.35	No trend	-193	0.57	No trend	479.0	0.26	No trend
Dyce	35.0	0.82	No trend	103	0.48	No trend	22	0.87	No trend	36.0	0.79	No trend
East Bergholt	142.0	0.37	No trend	230	0.06	No trend	46	0.55	No trend	94.0	0.20	No trend

Eastbourne	521.0	0.09	No trend	264	0.46	No trend	141	0.64	No trend	-79.0	0.84	No trend
Edinburgh	268.0	0.06	No trend	307	0.03	Trend	97	0.38	No trend	-56.0	0.71	No trend
Eskdalemuir	1165.0	0.00	Trend	1021	0.00	Trend	792	0.00	Trend	1227.0	0.00	Trend
Glenlee	428.0	0.00	Trend	416	0.00	Trend	331	0.01	Trend	421.0	0.00	Trend
Hastings	68.0	0.54	No trend	-85	0.55	No trend	-175	0.17	No trend	-130.0	0.33	No trend
Hawarden Bridge	38.0	0.77	No trend	70	0.53	No trend	-53	0.54	No trend	-94.0	0.39	No trend
Hayling Island	140.0	0.35	No trend	130	0.39	No trend	115	0.24	No trend	182.0	0.18	No trend
Heathrow	-356.0	0.01	Trend	-333	0.02	Trend	-29	0.76	No trend	-40.0	0.70	No trend
High Mowthorpe	143.0	0.26	No trend	-74	0.60	No trend	74	0.53	No trend	145.0	0.20	No trend
Hull	153.0	0.48	No trend	-8	0.97	No trend	-105	0.41	No trend	128.0	0.23	No trend
Hurn	-168.0	0.10	No trend	-187	0.21	No trend	-161	0.24	No trend	8.0	0.96	No trend
Inverness	85.0	0.39	No trend	135	0.41	No trend	170	0.23	No trend	113.0	0.27	No trend
Keele	-32.0	0.78	No trend	-13	0.93	No trend	91	0.41	No trend	70.0	0.49	No trend
Kielder Castle	428.0	0.02	Trend	452	0.01	Trend	468	0.00	Trend	592.0	0.00	Trend
Kilnochewe	153.0	0.21	No trend	326	0.00	Trend	269	0.07	No trend	135.0	0.34	No trend
Leadhills	617.0	0.00	Trend	688	0.00	Trend	559	0.00	Trend	579.0	0.00	Trend
Leckford	155.0	0.14	No trend	2	0.99	No trend	-47	0.65	No trend	50.0	0.68	No trend
Lerwick	269.0	0.11	No trend	27	0.87	No trend	205	0.24	No trend	683.0	0.00	Trend
Leuchars	114.0	0.36	No trend	261	0.08	No trend	-67	0.61	No trend	213.0	0.12	No trend
Lyneham	-110.0	0.44	No trend	-253	0.10	No trend	-138	0.25	No trend	-112.0	0.31	No trend
Lyonshall	200.0	0.12	No trend	161	0.21	No trend	131	0.39	No trend	247.0	0.03	Trend
Malham Tarn	139.0	0.34	No trend	186	0.20	No trend	290	0.01	Trend	345.0	0.02	Trend
Malvern	41.0	0.83	No trend	467	0.05	Trend	618	0.08	No trend	416.0	0.19	No trend
Morpeth	111.0	0.45	No trend	32	0.83	No trend	140	0.27	No trend	211.0	0.12	No trend
Newton Rigg	80.0	0.82	No trend	358	0.35	No trend	-205	0.58	No trend	41.0	0.91	No trend
Nottingham	-259.0	0.07	No trend	-167	0.23	No trend	-115	0.41	No trend	80.0	0.45	No trend
Oxford	-79.0	0.92	No trend	1031	0.22	No trend	375	0.22	No trend	-628.0	0.31	No trend
Paisley	848.0	0.01	Trend	731	0.07	No trend	373	0.21	No trend	750.0	0.06	No trend
Penicuik	97.0	0.50	No trend	144	0.32	No trend	-62	0.64	No trend	15.0	0.92	No trend
Plymouth	-329.0	0.03	Trend	-357	0.00	Trend	-204	0.08	No trend	-293.0	0.03	Trend
Ronaldsway	50.0	0.71	No trend	56	0.70	No trend	-25	0.85	No trend	122.0	0.34	No trend
Rothamsted	516.0	0.11	No trend	260	0.39	No trend	19	0.92	No trend	-33.0	0.89	No trend
Sheffield	739.0	0.15	No trend	915	0.07	No trend	717	0.16	No trend	1120.0	0.03	Trend
Slapton	321.0	0.03	Trend	157	0.28	No trend	-104	0.45	No trend	-115.0	0.37	No trend
Stormont	25.0	0.87	No trend	23	0.88	No trend	22	0.88	No trend	148.0	0.28	No trend
Stornoway	-18.0	0.95	No trend	26	0.93	No trend	-137	0.54	No trend	326.0	0.29	No trend
Threave	79.0	0.48	No trend	88	0.55	No trend	91	0.43	No trend	214.0	0.14	No trend
Tiree	232.0	0.11	No trend	38	0.80	No trend	141	0.10	No trend	283.0	0.16	No trend
Waddington	-52.0	0.76	No trend	48	0.82	No trend	-45	0.65	No trend	-103.0	0.35	No trend
Wick	-353.0	0.19	No trend	19	0.94	No trend	11	0.96	No trend	-10.0	0.96	No trend
Wisley	587.0	0.09	No trend	261	0.47	No trend	-355	0.27	No trend	-264.0	0.40	No trend

Table 5: Intense rainfall scenarios: Summary of the stations where statistically significant trends have been identified.

Group	Number of Stations	>25mm/day		2 Day>40mm		3 Day>60mm		7 Day>80mm	
		Trend	No Trend	Trend	No Trend	Trend	No Trend	Trend	No Trend
Group 1 Stations	5	Benmore Eskdalemuir Glenlee Leadhills	Kilnochewe	Benmore Eskdalemuir Glenlee Kilnochewe Leadhills	No stations	Benmore Eskdalemuir Glenlee Leadhills	Kilnochewe	Benmore Eskdalemuir Glenlee Leadhills	Kilnochewe
Group 2 Stations	5	Ardtalnaig Kielder Castle	Alwen Malham Tarn Threave	Ardtalnaig Kielder Castle	Alwen Malham Tarn Threave	Ardtalnaig Kielder Castle Malham Tarn	Alwen Threave	Ardtalnaig Kielder Castle Malham Tarn	Alwen Threave
Group 3 Stations	46	Heathrow* Paisley Plymouth* Slapton	42 stations	Edinburgh Heathrow* Malvern* Plymouth*	42 stations	No stations	46 stations	Bowhill Bute Rothesay Lerwick Lyonshall Plymouth* Sheffield	40 stations

Note: * The trends for Heathrow, Malvern and Plymouth are negative i.e. decreasing over time.

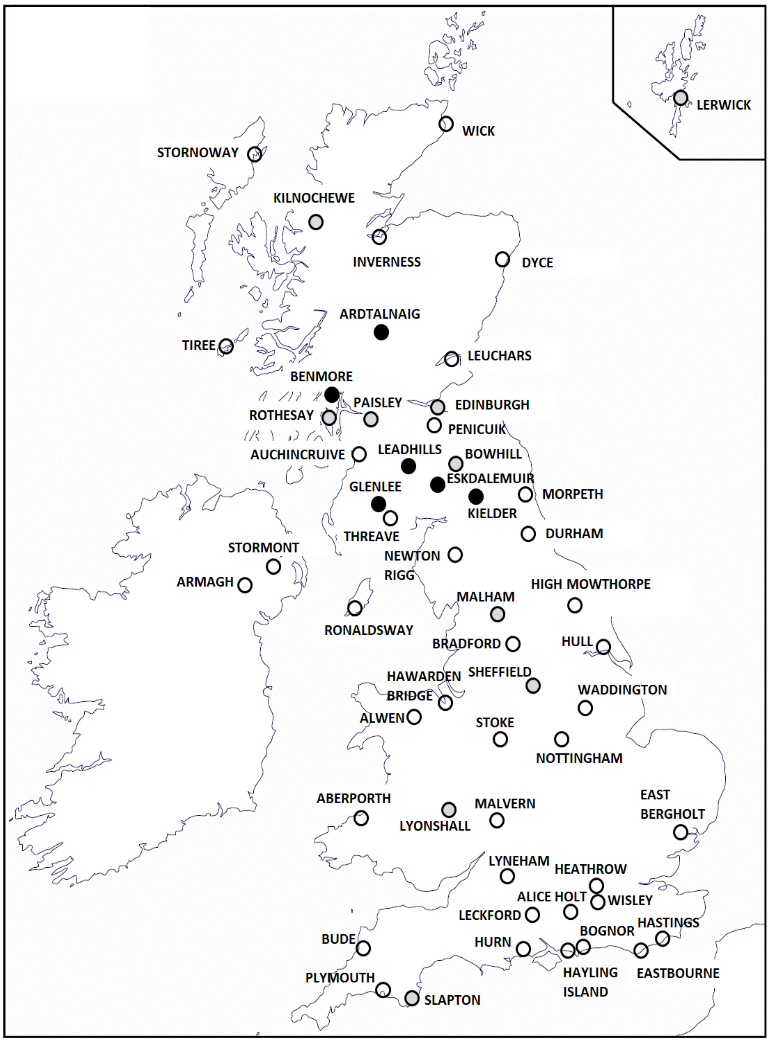

Figure 7: Stations used in this analysis: Black circles indicate statistically significant positive trends for all 4 rainfall intensity scenarios, grey circles indicate positive trends for 1 or 2 of the scenarios, and white circles indicate no statistically significant positive trends.

In general, there has been no statistically significant change in the intense rainfall scenario frequency for most Group 3 stations (the exceptions are shown in Table 5). However, negative (decreasing trends for found at Heathrow, Malvern and Plymouth).

The rate of change for those Group 1 and 2 stations with positive trends, as measured by the Sen's slope value, is shown in Table 6:

- The most rapid changes have occurred at Benmore, Glenlee and Leadhills where the frequency of all 4 scenarios has increased at over 1.5 additional event per decade. At Kilnochewe the 2 Day>40mm scenario has increased at 1.33 additional events per decade.
- At Ardtalnaig, Eskdalemuir and Kielder Castle the increase has typically been between 0.5 and 1 additional event per decade.
- The largest increase in frequency has been for scenario 4, with over 5 additional events per decade record for Benmore and Leadhills.

In this paper the "statistical significance" of two different hypotheses has been tested; no monotonic trend (the null hypothesis) and a monotonic trend. The compatibility of these two hypotheses with the recorded daily rainfall data is described by a test statistic (the S statistic) and a p-value. If the p-value falls below the pre-defined cut-off threshold of 0.05 (alpha) then the null hypothesis is rejected and the presence of a trend is described as "statistically significant". Some issues associated with the use of p-values in statistical significance testing are presented in Lee et al. [23], and will not be repeated here.

A positive trend of increasing intense rainfall event frequency is not present across the UK except at some (not all) upland stations. As a result, 20th century landslide activity in much of the UK should not be seen in the context of long-term changes in the frequency of intense rainfall; the time series has had short-term variability but over the longer term it has probably remained statistically stationary.

There has been a clear increase in the frequency of the intense rainfall scenarios at many (not all) stations in the Scottish Highlands and Southern Uplands, and the Northern Pennines. The most rapid changes have occurred at Benmore, Glenlee and Leadhills where the frequency of all 4 scenarios has increased at over 1.5 additional event per decade (Table 6). The positive trend in the Scottish Highlands is consistent with the findings of Barnett et al. [24], who found that heavy rainfall events over 10 mm/day have increased in winter, particularly in northern and western regions of Scotland (1961-2004; statistically significant where alpha=0.01; note that 10 mm/day is a less intense event than used in this analysis and would plot below Winter et al. [7], threshold line shown in Figure 1).

Table 6: Intense rainfall scenarios: Rate of increase in scenario frequency for stations with statistically significant positive trends.

Station	Group	Sen's Slope Value (Increase in Event Frequency/Decade)*			
		>25mm/Day	2 Day>40mm	3 Day>60mm	7 Day>80mm
Ardtalnaig	2	0.56	1.04	0.79	3.3
Benmore	1	1.89	2.79	2.34	5.45
Bute Rothesay	3	N/A	N/A	N/A	1.4
Edinburgh	3	N/A	0.50	N/A	N/A
Eskdalemuir	1	0.80	0.71	0.5	2.18
Glenlee	1	1.54	1.67	1.03	3.64
Kielder Castle	2	0.81	1.0	0.67	2.71
Kilnochewe	1	N/A	1.33	N/A	N/A
Leadhills	1	1.60	4.79	1.54	5.29
Lerwick	3	N/A	N/A	N/A	0.34
Malham Tarn	2	N/A	N/A	0.46	1.91
Paisley	3	0.17	N/A	N/A	N/A
Slapton	3	0.38	N/A	N/A	N/A

Note: * The trends for Heathrow, Malvern and Plymouth are negative i.e. decreasing over time.

Whilst temperatures across the UK have increased by over 1°C over the last century, this does not appear to have led to an increase in extreme rainfall event frequency except in the Scottish Highlands and Southern Uplands, and the Northern Pennines. These changes in upland UK have been noted by other researchers. For example, Otto et al. [25], estimated that the frequency of intense rainfall events in northern England and southern Scotland (such as the December 2015 storm Desmond with 341.4 mm of rainfall in 24-hours) had increased by 59% (albeit with broad confidence limits around this value) over the last century or so. Burt et al. [26], undertook an analysis of rain gauge records along a transect across northern England (including the Lake District and the Pennines) and found that the frequency of heavy falls per decade had increased at the upland sites (e.g. Ambleside), but not at lowland sites such as Barrow and Durham. On the other hand, Dawson et al. [27], analyzed the frequency of historical storms in Scotland since the 19th century and found no increase in storm occurrence.

It remains unclear, however, about the extent to which the stations included in this analysis are representative of the UK as a whole. Indeed, the rain-gauge network is biased in the sense that the focus is mainly on flood forecasting and synoptic purposes and that remote mountain areas with mean annual rainfall >2500 mm are under-represented (e.g. Rodda et al. [12], McGregor et al. [28]). For example, it is entirely possible that sites at higher altitude in the west of Scotland have experienced a more rapid increase in event frequency than that detected in this analysis. Perhaps it could be argued that there is a split between upland UK (in the north and west) and lowland UK in terms of changing rainfall patterns.

It is also important to emphasize that this analysis has focused on the historical trends in selected intense rainfall scenarios. Although these scenarios are relevant to debris flow triggering in parts of Scotland (see Figure 1), whether they have represented shallow landslide triggering events over the rest of the UK is uncertain. More detailed research of the kind undertaken by Winter and his co-workers linking landslide events to rainfall thresholds in Scotland is clearly needed for other parts of the UK.

Lee et al. [23], presented an analysis of long-term trends in annual and winter effective rainfall in the UK, concluding that for much of the country there have been no statistically significant changes in effective rainfall. The exception to this pattern was in Scotland (except the east coast) which appears to have experienced significant increases in both annual and winter effective rainfall. These findings are similar to those presented in this paper. It follows that there is no simple picture for the recent rainfall trends across whole of the country; parts of Scotland have experienced statistically significant changes in rainfall–both the frequency of intense rainfall events and annual and winter effective rainfall–whilst for the rest of the UK the rainfall time series has probably been close to being stationary (i.e. parameters such as mean and variance do not change over time) or cyclic (e.g. related to natural variations in the North Atlantic Oscillation; e.g. Allan et al. [29], Jones et al. [30], and Marsh et al. [31]. However, even under a stationary time series, extreme events do occur.

CONCLUSION

Intense rainfall events are important controls on landslide activity in the UK, but there is significant spatial variation in long-term trends. A positive trend of increasing intense rainfall event frequency is not present across the UK. The overall conclusion that there is no uniform pattern across the UK is consistent with the findings of previous studies. For example, in an assessment of changes in seasonal and annual extreme rainfall trends in the UK: "The magnitude of changes in estimated return periods (of seasonal and annual extremes) are spatially varied, and dominated in northern and western parts of the UK by a periodic forcing such as the North Atlantic Oscillation (NAO), superimposed on normal seasonal fluctuations."

ACKNOWLEDGEMENT

A big thank you to those friends who took the time to read an earlier draft of the paper. Your comments and encouragements were much appreciated. Special thanks to Mike Winter who took the time to comment on an early draft and explain the various studies that he and his colleagues had undertaken in Scotland.

REFERENCES

1. Gibbs NM, Gibbs SV. Misuse of 'trend'to describe 'almost significant'differences in anaesthesia research. Br J Anaesth. 2015;115(3):337-339.
2. Hutchinson JN. Landslides in Britain and their countermeasures. Landslides. 1984;21(1):1-25.
3. Jones DK, Lee EM. Landsliding in Great Britain. HMSO London. 1994.
4. Lee EM, Giles DP. Chapter 4 Landslide and slope stability hazard in the UK. Geol Soc Eng Geol Spec Publ. 2020;29(1):81-162.
5. Winter MG. Chapter 5 Debris flows. Geol Soc Eng Geol Spec Publ. 2020;29(1):163-185.
6. Corominas J. Landslides and climate. In Proceedings of the 8th International Symposium on Landslides. 2000;4:1-33.
7. Winter MG, Dent J, Macgregor F, Dempsey P, Motion A, Shackman L. Debris flow, rainfall and climate change in Scotland. Q J Eng Geol Hydrogeol. 2010;43:429-446.
8. Pennington C, Dijkstra T, Lark M, Dashwood C, Harrison A, Freeborough K. Antecedent precipitation as a potential proxy for landslide incidence in South West United Kingdom. In Landslide Science for a Safer Geoenvironment. 2014;1:253-259.
9. Winter MG, Ognissanto F, Martin LA. Rainfall thresholds for landslides: Deterministic and probabilistic approaches. TRL Report. 2019.
10. McMillan FN, Holt CA. BEAR Scotland NW trunk road maintenance: Efficient management of geotechnical emergencies. Q J Eng Geol Hydrogeol. 2019;52(3):286-294.
11. Winter MG, Wong JC. The assessment of quantitative risk to road users from debris flow. Geoenvironmental Disasters. 2020;7:1-19.
12. Rodda JC. Rainfall excesses in the United Kingdom. Trans Inst Br Geogr. 1970;63:49-60.
13. Hand WH, Fox NI, Collier CG. A study of twentieth-century extreme rainfall events in the United Kingdom with implications for forecasting. Meteorol Appl. 2004;11(1):15-31.

14. Bleasdale A, Douglas CK. Storm over Exmoor on August 15, 1952. Met Mag. 1952;81:353-367.

15. Golding B, Clark P, May B. The Boscastle flood: Meteorological analysis of the conditions leading to flooding on 16 August 2004. Weather. 2005;60(8):230-235.

16. Hulme M, Barrow E. Climates of the British Isles: Present, past and future. Psychol Press. 1997.

17. Mann HB. Nonparametric tests against trend. Econometrica. 1945;13:245-59.

18. Kendall MG. Rank correlation methods. Charles Griffin, London. 1975.

19. Gilbert RO. Statistical methods for environmental pollution monitoring. John Wiley and Sons. 1987.

20. Hamed KH, Rao AR. A modified Mann-Kendall trend test for autocorrelated data. J Hydrol. 1998;204(1):182-196.

21. Fatichi S, Barbosa SM, Caporali E, Silva ME. Deterministic versus stochastic trends: Detection and challenges. J Geophys Res Atmos. 2009;114:D18.

22. Sen PK. Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc. 1968;63(324):1379-1389.

23. Lee EM. Statistical analysis of long-term trends in UK effective rainfall: Implications for deep-seated landsliding. Q J Eng Geol Hydrogeol. 2020;53(4):587-597.

24. Barnett C, Hossell J, Perry M, Procter C, Hughes G. Patterns of climate change across Scotland: Technical Report. In SNIFFER Project CC03. 2006.

25. Otto FE, van der Wiel K, van Oldenborgh GJ, Philip S, Kew SF, Uhe P, et al. Climate change increases the probability of heavy rains in Northern England/Southern Scotland like those of storm Desmond—a real-time event attribution revisited. Environ Res Lett. 2018;13(2):024006.

26. Burt TP, Ferranti EJ. Changing patterns of heavy rainfall in upland areas: A case study from northern England. Int J Climatol. 2012;32(4):518-532.

27. Dawson AG, Warren J, Gomez C, Ritchie W. Weather and coastal flooding history: The Uists and Benebecula, 2011. University of Aberdeen. 2011:45.

28. McGregor P, MacDougall K. A review of the Scottish rain-gauge network. In Proceedings of the Institution of Civil Engineers-Water Management. 2009;162(2):137-146.

29. Allan R, Tett S, Alexander L. Fluctuations in autumn–winter severe storms over the British Isles: 1920 to present. Int J Climatol. 2009;29(3):357-371.

30. Jones MR, Fowler HJ, Kilsby CG, Blenkinsop S. An assessment of changes in seasonal and annual extreme rainfall in the UK between 1961 and 2009. Int J Climatol. 2013;33(5):1178-1194.

31. Marsh T, Kirby C, Muchan K, Barker L, Henderson E, Hannaford J. The winter floods of 2015/2016 in the UK-a review. NERC. 2016.