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Technical Note No. 68

ESTIMATION OF POINT RAINFALL FREQUENCIES IN IRELAND

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Disclaimer

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1. Introduction

In Ireland, short-duration and intense localised rainfall events can lead to severe flooding (e.g. Lennon and Walsh, 2008). In upland areas, heavy rainfall events are associated with slope instability, erosion, landslides, sediment transport, destabilisation of masses of peat and flooding. Runoff events associated with rainfall extremes often result in flash flooding, particularly in small drainage basins with short concentration times and rapid response catchments. Such events present a significant risk to human life and infrastructure, especially in densely populated urban settings. Moreover, current research shows that extreme rainfall events are projected to increase (Nolan and Flanagan, 2020; IPCC, 2021).

Estimating the return levels of rainfall thresholds for specific return periods has diverse applications, such as informing the design criteria for drainage schemes, sewerage systems, bridges, gutters, and fluvial flood mitigation measures (e.g. Tank *et al*., 2009; CEN, 2000; BSI, 2007; Ministry of Housing, Communities & Local Government, 2015; Department of Housing, Planning, Community and Local Government, 2016). It is not always economically viable to design systems capable of withstanding all potential extreme rainfall events (Logue, 1975). It is, however, common practice to design systems in such a way as to accommodate a rainfall amount likely to be exceeded only once in a specified number of years, a terminology known as the return period (Logue, 1975). Analysing the extremes of rainfall thresholds through the calculation of return values for specific return periods constitutes an optimum balance between taking on high safety standards that are very expensive and preventing major damage to infrastructures from extreme events that are likely to occur during the useful life of such infrastructures (Tank *et al*., 2009). In general, the longer the return period, the greater the rainfall intensity for which allowance must be made. The annual exceedance probability for a particular duration is the probability of exceeding a specified rainfall amount at least once in any year. The return period of a particular rainfall threshold constitutes the average number of years which must pass before the threshold is equalled or exceeded. The length of the return period for a particular rainfall threshold constitutes the probability of occurrence of an intense event. For instance, a 50-year return period corresponds to an annual exceedance probability of 0.02.

Previous estimations of rainfall frequencies for Ireland were produced by Morgan (1953), Logue (1971, 1975) and Fitzgerald (2007). Using the depth-duration-frequency method employed by Fitzgerald (2007), this study generates return values for various return periods (2, 5, 10, 20, 50, 100 and 120 years) for specific rainfall thresholds ranging from 1 to 25 days and from 15 minutes to 24 hours. This research updates the work carried out by Fitzgerald (2007) by employing a denser network of stations with data up to 2021. These outputs are paramount to enhancing resilience in support of climate change adaptation. For example, a rainfall duration of a few minutes may be critical for the production of floods in the case of the drainage of a small area, whereas a rainfall duration of several days may be significant for the flooding event of a large river. The outputs of this research will benefit a wide range of stakeholders currently collaborating with Met Éireann, such as the National Standards Authority of Ireland, the Office of Public Works and Transport Infrastructure Ireland. This report will also inform policy in delivering key national infrastructure such as housing and building renovation.

A brief description of rainfall in Ireland is presented in section 1.1. Section 2 presents the data used in the analysis. The methodology is outlined in section 3 and comprises an explanation of the conversion from fixed to sliding durations, the depth-duration (DDF) model applied for durations ranging from 15 minutes to 24 hours and from 1 to 25 days, the gridding techniques and the application for deriving rarity estimates of rainfall with less than 15 minutes duration. Section 4 presents the discussion and section 5 highlights the conclusion.

1.1. Rainfall in Ireland

Ireland is located at the eastern edge of the North Atlantic between latitude 51°N and 56°N, longitude 5°W and 11°W. It has an area of about 84,000km^2. The elevation is generally less than 150m above mean sea level in the central plain. The main mountains have peaks above 600m, with the highest mountain (Carrauntoohil in Co. Kerry) at 1041m above sea level. About 240km^2 of the country's area lies above 600m above sea level, and about 4100km^2 lies between 300 and 600m above sea level (Rohan, 1975, citing Roberts, 1967).

The climate of Ireland is distinguished as mild and maritime by the influence of the North Atlantic Ocean to the north, west and south and the Irish Sea to the east of the country. The North Atlantic Current diminishes the air temperature range in Ireland; therefore, extremes in summer and winter seasons are less intense compared to more continental countries at similar latitudes. The westerly atmospheric circulation of the middle latitudes constitutes another major control of Ireland's climate. The centres of depressions track across the North Atlantic, and the majority pass to the northwest of Ireland.

Precipitation in Ireland occurs mainly as rain or drizzle. Rainfall is variable temporally and spatially. The variation in the annual mean rainfall between coastal and inland areas and higher and lower altitudes is evident (Figure 1). Annual rainfall totals of over 3000mm are observed in the hilly and mountainous areas in the west. In contrast, the midlands receive over 800mm, and the sheltered areas in the east sustain over 600mm.

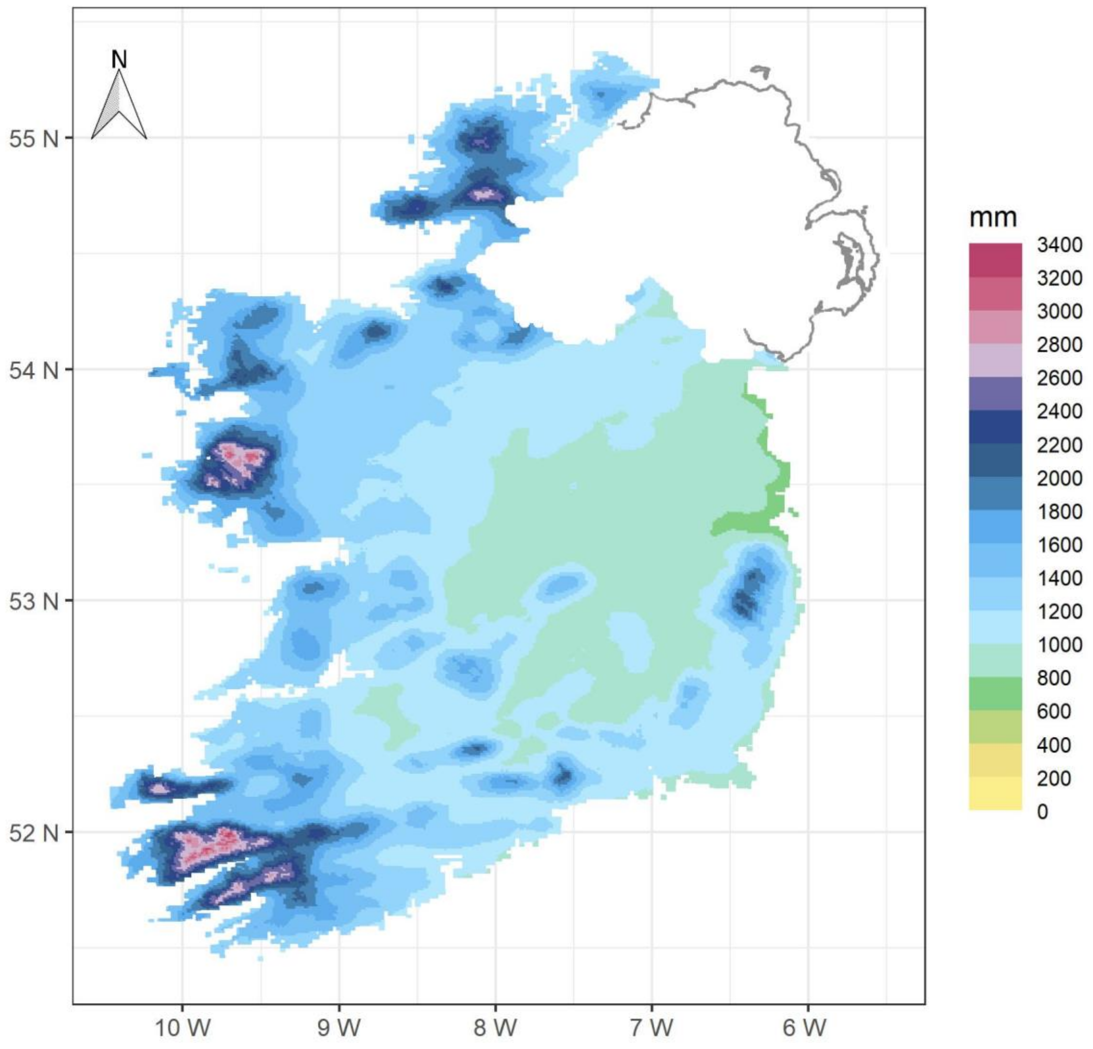

Figure 1: Mean annual rainfall (mm) for the climate normal 1991 – 2020 in the Republic of Ireland.

Rainfall events can originate from the passage of extratropical cyclones or frontal zones, orographic and convective processes. Cyclonic rainfall corresponds to the greater part of the average annual rainfall and namely in the west of the country. Heavy rainfalls of a few hours or 1-day or 2-days duration are commonly associated with extratropical cyclones and frontal systems affecting large areas or the whole country. The average annual rainfall has a west-to-east decreasing gradient since most of the extratropical cyclones have a trajectory to the northwest of Ireland and their associated fronts across the country, providing more rain in the west and northwest areas than in the south and east. Nevertheless, cyclones can sometimes pass close to the south and southeast of the country and bring heavy rainfall to the south and east areas. Persistent rainfall events are associated with slow moving depressions and fronts and can range from several hours to a day or days. Persistent rainfall can result in soils near saturation; therefore, the ground has little or no capacity to absorb excessive amounts of rainfall and can be associated with flooding events.

Rainfall in Ireland is mainly characterised by low-intensity and long-duration events (Fitzgerald, 2007). Nevertheless, short-duration and intense rainfall events have occurred (e.g. Lennon and Walsh, 2008; Met Éireann, 2011; Walsh, 2010). Extreme rainfall with durations of 60 minutes or less is often associated with individual and localised thunderstorms related to brief convective systems of small horizontal extent due to vertical instability in the atmosphere. The sea surface tends to be warmer than the land in the winter, and convective clouds form mostly over the sea. As the prevailing winds in Ireland are from a westerly direction, convective rainfall, which falls in the west of the country, comes from convective processes that originated over the sea. In contrast, in the summer, the land is warmer than the sea surface, and most of the convective activity occurs over land. In the midlands and eastern areas, convective rainfall events have a maximum during summer. However, these convective systems may be embedded in larger rain-producing systems. Sub-daily rainfall extremes ranging from 15 minutes are associated with convective processes that are often linked with thunderstorms and are more frequent during the summer and autumn.

Regarding the extreme rainfall totals since 1942, the highest hourly total on record is 52.2mm at Clonroche, Co. Wexford on the 27th of June 1986 (Met Éireann, 2023) which resulted from an outbreak of thundery rain (Met Éireann, 1986). In the same period, the highest daily total was 243.5mm at Cloone Lake in Co. Kerry on the 18th of September 1993 as depressions tracked to the south of the country (Met Éireann, 1993). The highest monthly rainfall total was 943.5mm, registered in December 2015 at Gernapeka in Co. Cork. The impacts of the storms Desmond, Eva and Frank resulted in persistent rainfall in December 2015 (Met Éireann, 2015).

2. Meteorological data

2.1. Daily rainfall data (0900 – 0900 UTC)

A total of 728 stations in Ireland with quality-controlled daily rainfall total covering the period from 1941 to 2021 were employed in the data analysis, with lengths ranging from 30 to 81 years (Figure 2). A further 24 stations in Northern Ireland covering the period from 1853 to 2021 were used, with periods ranging from 30 to 169 years to improve the outputs in the border (Figure 2). The observations from stations in Ireland were obtained from the National Climate Archive at Met Éireann. The series from stations in Northern Ireland were downloaded from the Centre for Environmental and Data Analysis (CEDA) Archive (Met Office, 2022).

Rainfall is recorded at climate and synoptic stations and through a network of voluntary rainfall observers. At climate and voluntary rainfall stations, a daily rainfall total is recorded each day at 0900 UTC, and the total recorded at this time is assigned to the previous day. At synoptic stations, rainfall readings are continuously reported on the hour.

The annual maxima of the 0900 – 0900 UTC daily rainfall observations were extracted for eleven durations ranging from 1 to 25 days for each year and per station (Table 1) following a block maxima approach (Coles, 2001). Using the calendar year from January to December to calculate the annual maxima rainfall can mean those rainfall events, which can often span the transition between one year and the next, can be lost when identifying the annual maxima. Therefore, following the methodology of Fitzgerald (2007), the period from April to March was used as the rainfall year to avoid this end-of-year effect.

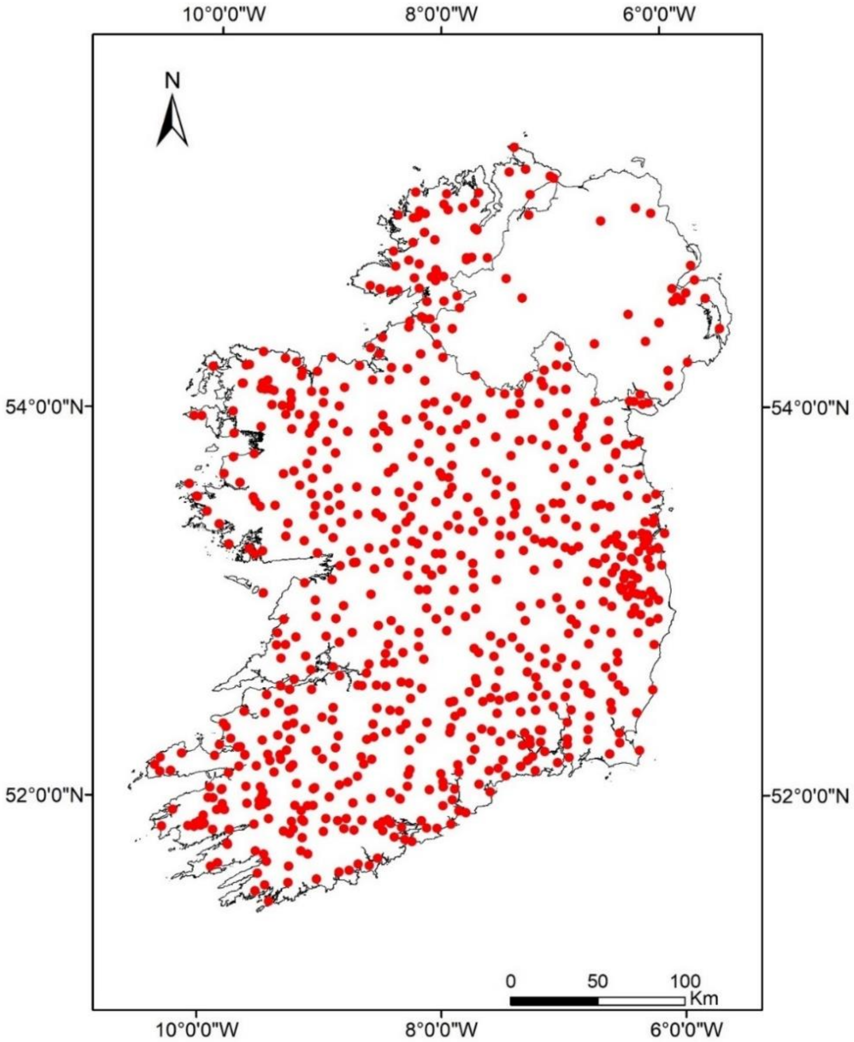

Figure 2: Location of the stations with daily rainfall observations on the island of Ireland.

Table 1: Annual maxima of the 0909 – 0900 UTC daily rainfall observations extracted for eleven durations ranging from 1 to 25 days.

Durations											
Day	1	2	3	4	6	8	10	12	16	20	25

2.2. Short-duration rainfall data

The maxima of all short-duration rainfall observations attaining to or exceeding at least one of a set of thresholds for durations between 15 minutes and 24 hours were extracted on an individual station basis for each year (Table 2) according to a block maxima approach (Coles, 2001). The observations are available for 38 stations in Ireland and for lengths ranging from 33 to 71 years in the period from 1946 to 2021 (Figure 3, Table 3). No short-duration falls were available for stations in Northern Ireland.

These short-duration observations (Table 3) can begin at any arbitrary time. For instance, the maxima correspond to the value reached over any 60-minute period rather than over fixed clock hours (Logue, 1975). The date of the short-duration rainfall is assigned to the day on which most or all of the total rainfall event was recorded.

The sub-daily rainfall maxima are used to test the sub-daily DDF model for durations ranging from 15 minutes to 24 hours, as explained in section 3.2.2.

The short-duration falls for manual stations in Ireland were extracted from rain charts obtained in the Dines Tilting Syphon rainfall recorder. However, since the mid-nineties, the Dines Tilting Syphon rainfall recorder has been replaced by tipping-buckets gauges at some stations. Fitzgerald (2007) analysed the periods of overlap between the Dines Tilting Syphon recorder charts and the tipping-buckets gauges and found the differences to be generally small. Therefore, no adjustment for the transition was made in this report. These rainfall charts are autographic records, also known as hyetograms, representing the duration, intensity and amount of rainfall periods.

Table 2: The maxima of all falls attaining or exceeding at least one set of thresholds for durations between 15 minutes and 24 hours extracted.

Duration	15 min	30 min	1 hour	2 hours	3 hours	4 hours	6 hours	12 hours	24 hours
Threshold (mm)	4.0	5.0	6.0	10.0	12.5	15.0	20.0	25.0	30.0

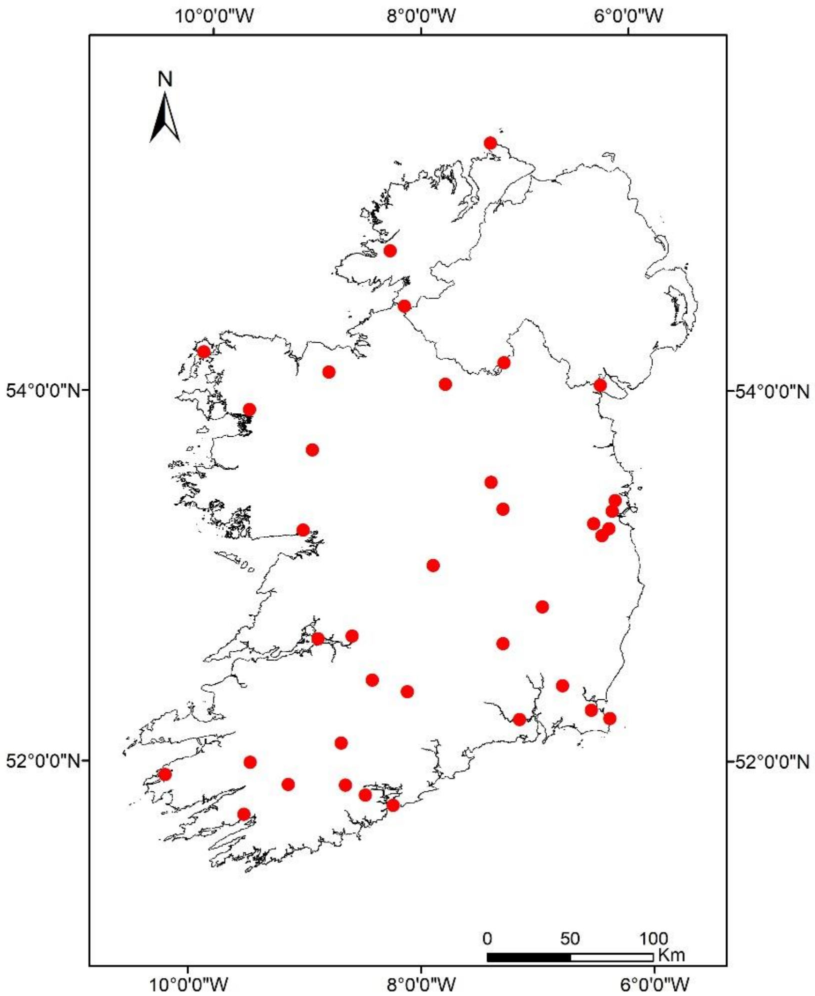

Figure 3: Location of the stations with short-duration rainfall observations in Ireland.

Table 3: Meteorological stations and respective elevation, geographical coordinates and period covered by the short-duration rainfall observations.

Name	Station number	Elevation (m)	Latitude (°)	Longitude (°)	Period	Years
Ardnacrusha (Gen. Stn. No.2)	4011	28	52.70639	-8.61444	1952 – 1998	47
Ballinamore	3337	82	54.06944	-7.77500	1964 – 2004	41
Ballyboden	6623	107	53.27639	-6.30417	1968 – 2000	33
Ballyshannon (Cherrymount)	3237	30	54.49194	-8.15417	1974 – 2018	45
Bansha Aherlow (W.W.)	5012	128	52.40694	-8.12222	1955 – 2018	64
Belmullet (manual)	1034	9	54.22778	-10.00694	1956 – 2013	66
Belmullet	2375		54.22750	-10.00694	2013 – 2021	
Birr	4919	72	53.09028	-7.89028	1956 – 2008	53
Casement	3723	91	53.30556	-6.43889	1958 – 2008	51
Claremorris	2727	69	53.71111	-8.99139	1958 – 2011	64
	2175	68	53.71083	-8.99250	2013 – 2021	
Clones	2437	89	54.18333	-7.23333	1950 – 2008	59
Clonroche	3015	116	52.43333	-6.74583	1963 – 2004	42
Cloonacool (Lough Easkey)	3135	204	54.13194	-8.84722	1954 – 2018	65
Cork Airport	3904	155	51.84722	-8.48611	1962 – 2002	41
Derrygreenagh	3431	90	53.39167	-7.25833	1956 – 2018	63
Dublin Airport	532	71	53.42778	-6.24083	1958 – 2021	64
Dundalk Annaskeagh (W.W.)	538	61	54.05194	-6.35139	1959 – 2017	59
Galway (Univ. Coll.)	3927	14	53.27639	-9.06389	1965 – 2000	36
Glasnevin	1823	21	53.37000	-6.27028	1950 – 2016	67
Glenasmole D.C.W.W.	1923	158	53.23889	-6.36667	1966 – 2004	39
Glengarriff	201	7	51.73472	-9.54583	1975 – 2017	43
Glenties Hatchery	441	44	54.79111	-8.28750	1957 – 2000	44
Hospital (VOC. SCH.)	4111	101	52.46944	-8.43056	1958 – 1994	37
Inishcarra	3704	24	51.90000	-8.66111	1954 – 2018	65
Johnstown Castle	915	49	52.29167	-6.50000	1951 – 2002	71
	475	52	52.29167	-6.50000	2008 – 2010	
	1775	62	52.29778	-6.49667	2011 – 2021	
Kilkenny	3613	65	52.66528	-7.26944	1957 – 2008	52
Killarney (Muckross House)	3205	58	52.01667	-9.49861	1968 – 2004	37
Macroom (Renaniree)	3723	198	53.30556	-6.43889	1958 – 2008	51
Newport Furnace	833	14	53.92333	-9.57111	1959 – 2016	63
Newport	1175	22	53.92361	-9.57278	2017 – 2021	

Table 3: Continued.

Name	Station number	Elevation (m)	Latitude (°)	Longitude (°)	Period	Years
Malin Head (manual)	545	22	55.37222	-7.33889	1957 – 2012	65
Malin Head	1575	20	55.37194	-7.33917	2010 – 2021	
Mallow (Sugar Factory)	2906	52	52.12639	-8.70278	1950 – 1985	36
Mullingar II	2922	101	53.53722	-7.36222	1958 – 2008	64
Mullingar	875				2003 – 2021	
Oak Park	375	62	52.86111	-6.91528	1967 – 2021	55
Roches Point	1075	40	51.79306	-8.24444	1955 – 2021	67
Rosslare	2615	26	52.25000	-6.33472	1958 – 2008	51
Shannon Airport	518	15	52.69028	-8.91806	1958 – 2004	47
Valentia Observatory (manual)	305	24	51.93806	-10.24333	1958 – 2015	64
Valentia Observatory	2275	24	51.93833	-10.24083	2012 – 2021	
Waterford (Tycor)	1812	49	52.25278	-7.13056	1946 – 1987	42

2.3. Hourly rainfall data

Hourly rainfall observations are available for 26 stations and lengths ranging from 10 to 80 years in the period from 1942 to 2021 (Figure 4, Table 4). The hourly rainfall total corresponds to the sum of the rainfall (mm) over the 60-minutes period. The hourly rainfall observations are applied to convert annual maxima from daily stations into hourly equivalents, which provides a more realistic value for the annual maxima totals. This procedure consists of converting fixed to sliding durations, described in section 3.1.

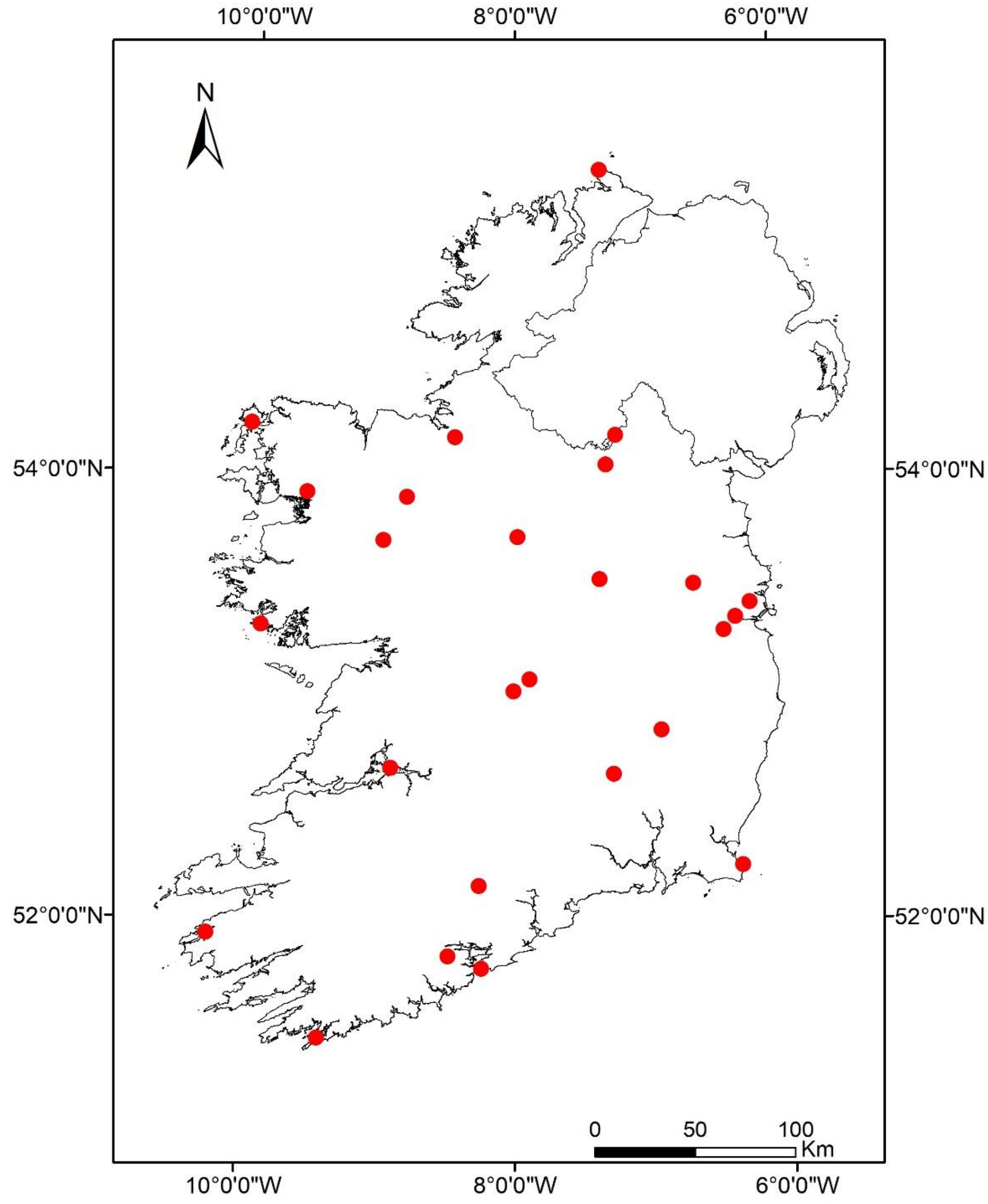

Figure 4: Location of the stations with hourly rainfall observations in Ireland.

Table 4: Meteorological stations and respective elevation, geographical coordinates and period covered by the hourly rainfall observations.

Name	Station number	Elevation (m)	Latitude (°)	Longitude (°)	Period	Years
Ballyhaise	675	78	54.0514	-7.30972	2004 – 2021	18
Belmullet	2375	9	54.2275	-10.00694	2012 – 2021	10
Birr	4919	72	53.0903	-7.89028	1955 – 2008	54
Casement	3723	91	53.3056	-6.43889	1964 – 2021	58
Claremorris	2175	68	53.7108	-8.99250	2011 – 2021	11
Clones	2437	89	54.1833	-7.23333	1951 – 2010	60
Cork Airport	3904	155	51.8472	-8.48611	1962 – 2021	60
Dublin Airport	532	71	53.4278	-6.24083	1942 – 2021	80
Dunsany	1375	83	53.5158	-6.66000	2007 – 2021	15
Gurteen	1475	75	53.0350	-8.00861	2008 – 2021	14
Kilkenny	3613	65	52.6653	-7.26944	1958 – 2007	50
Knock Airport	4935	201	53.9061	-8.81722	1997 – 2021	25
Mace Head	275	21	53.3258	-9.90083	2004 – 2021	18
Markree	1275	34	54.1750	-8.45556	2006 – 2021	16
Malin Head	1575	20	55.3719	-7.33917	2010 – 2021	12
Moore Park	575	46	52.1639	-8.26389	2004 – 2021	18
Mt Dillon	1975	39	53.7269	-7.98083	2005 – 2021	17
Mullingar	875	101	53.5372	-7.36222	2004 – 2021	18
Newport	1175	22	53.9236	-9.57278	2005 – 2021	17
Oak Park	375	62	52.8611	-6.91528	2004 – 2021	18
Phoenix Park	175	48	53.3636	-6.34972	2004 – 2021	18
Roches Point	1075	40	51.7931	-8.24444	2005 – 2021	17
Rosslare	2615	26	52.2500	-6.33472	1957 – 2006	50
Shannon Airport	518	15	52.6903	-8.91806	1946 – 2021	76
Sherkin Island	775	21	51.4764	-9.42778	2005 – 2021	17
Valentia Observatory	2275	24	51.9383	-10.24083	2011 – 2021	10

2.4. Minute rainfall data

The 1-minute rainfall observations are available for 21 stations in Ireland and have lengths ranging from 12 to 20 years in the period from 2002 to 2021 (Figure 5, Table 5). No observations were available for stations in Northern Ireland.

The minute rainfall observations are applied to generate rarity estimates for durations shorter than 15 minutes, specifically 2, 5 and 10 minutes duration described in section 3.4.

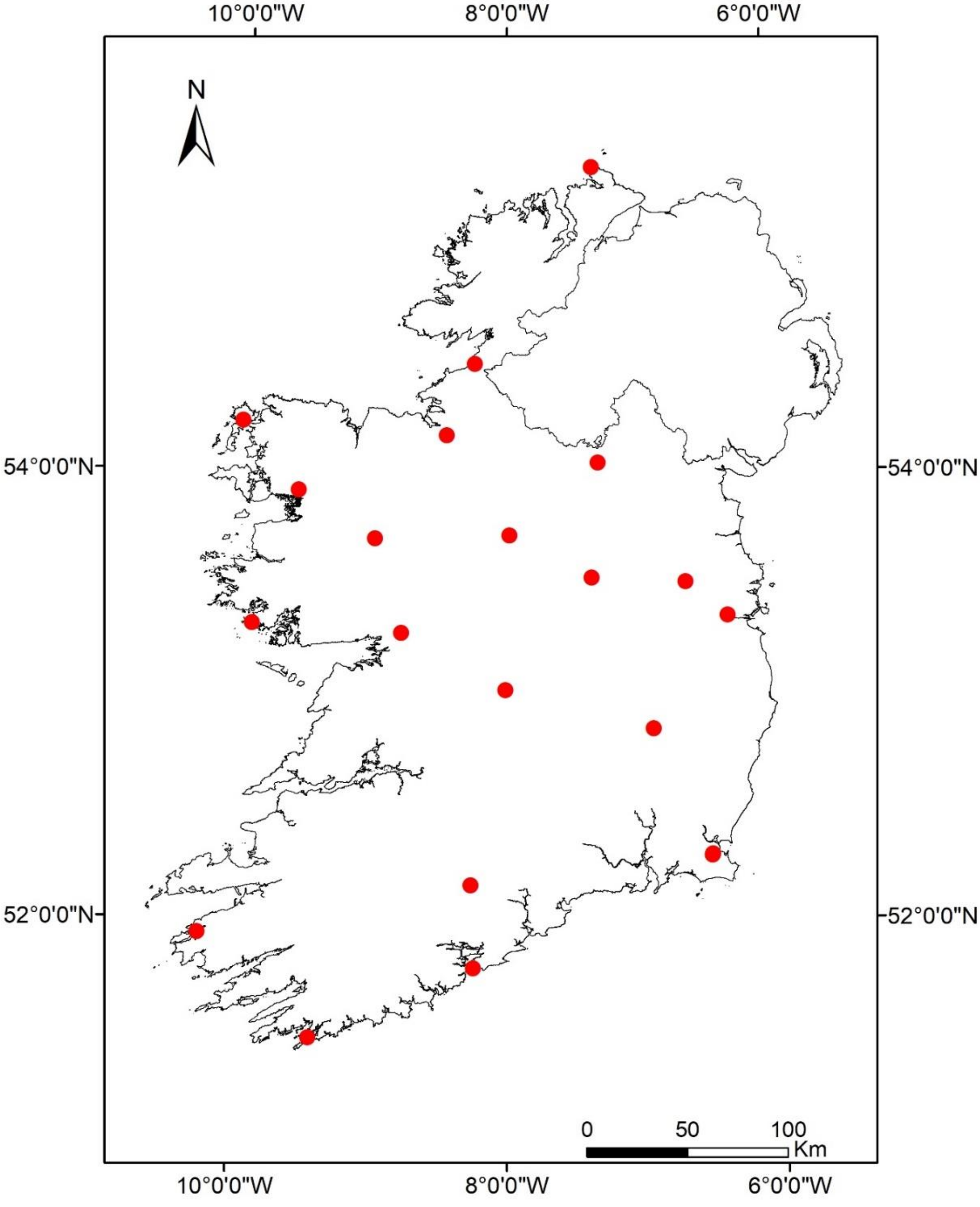

Figure 5: Location of the stations with 1-minute rainfall observations in Ireland.

Table 5: Meteorological stations and respective elevation, geographical coordinates and period covered by the 1-minute rainfall observations.

Name	Station number	Elevation (m)	Latitude (°)	Longitude (°)	Period	Years
Athenry	1875	40	53.28917	-8.78556	2010 – 2021	12
Ballyhaise	675	78	54.05139	-7.30972	2003 – 2021	19
Belmullet	2375	9	54.22750	-10.0069	2006 – 2021	16
Claremorris	2175	68	53.71083	-8.99250	2010 – 2021	12
Dunsany	1375	83	53.51583	-6.66000	2006 – 2021	16
Finner	2075	33	54.49389	-8.24306	2010 – 2021	12
Gurteen	1475	75	53.03500	-8.00861	2008 – 2021	14
Johnstown Castle	475	52	52.29167	-6.50000	2003 – 2020	18
Johnstown Castle II	1775	62	52.29778	-6.49667	2008 – 2021	14
Mace Head	275	21	53.32583	-9.90083	2003 – 2021	19
Malin Head	1575	20	55.37194	-7.33917	2009 – 2021	13
Markree	1275	34	54.17500	-8.45556	2004 – 2021	18
Moore Park	575	46	52.16389	-8.26389	2003 – 2021	19
Mt Dillon	1975	39	53.72694	-7.98083	2004 – 2021	18
Mullingar	875	101	53.53722	-7.36222	2002 – 2021	20
Newport	1175	22	53.92361	-9.57278	2005 – 2021	17
Oak Park	375	62	52.86111	-6.91528	2003 – 2021	19
Phoenix Park	175	48	53.36361	-6.34972	2003 – 2021	19
Roches Point	1075	40	51.79306	-8.24444	2004 – 2021	18
Sherkin Island	775	21	51.47639	-9.42778	2004 – 2021	18
Valentia Observatory	2275	24	51.93833	-10.2408	2010 – 2021	12

3. Methodology

The methodology section describes the depth-duration-frequency (DDF) model to produce the estimates of return period rainfall on a 2km grid for durations ranging from 15 minutes to 25 days following a methodological approach previously applied by Fitzgerald (2007). This section details the conversion of rainfall data from fixed to sliding durations, the DDF model, the DDF model for durations ranging from 1 to 25 days, the DDF model for durations ranging from 15 minutes to 24 hours, the average recurrence interval, implementation of the DDF model and gridding. The return periods are calculated for 2, 5, 10, 20, 50, 100 and 120 years. The application for deriving rarity estimates considering the proportion of the 15-minute duration rainfall distributed by the 10, 5 and 2 minutes duration rainfall is explained. The workflow of the methodology employed in this report is summarised in Figure 6.

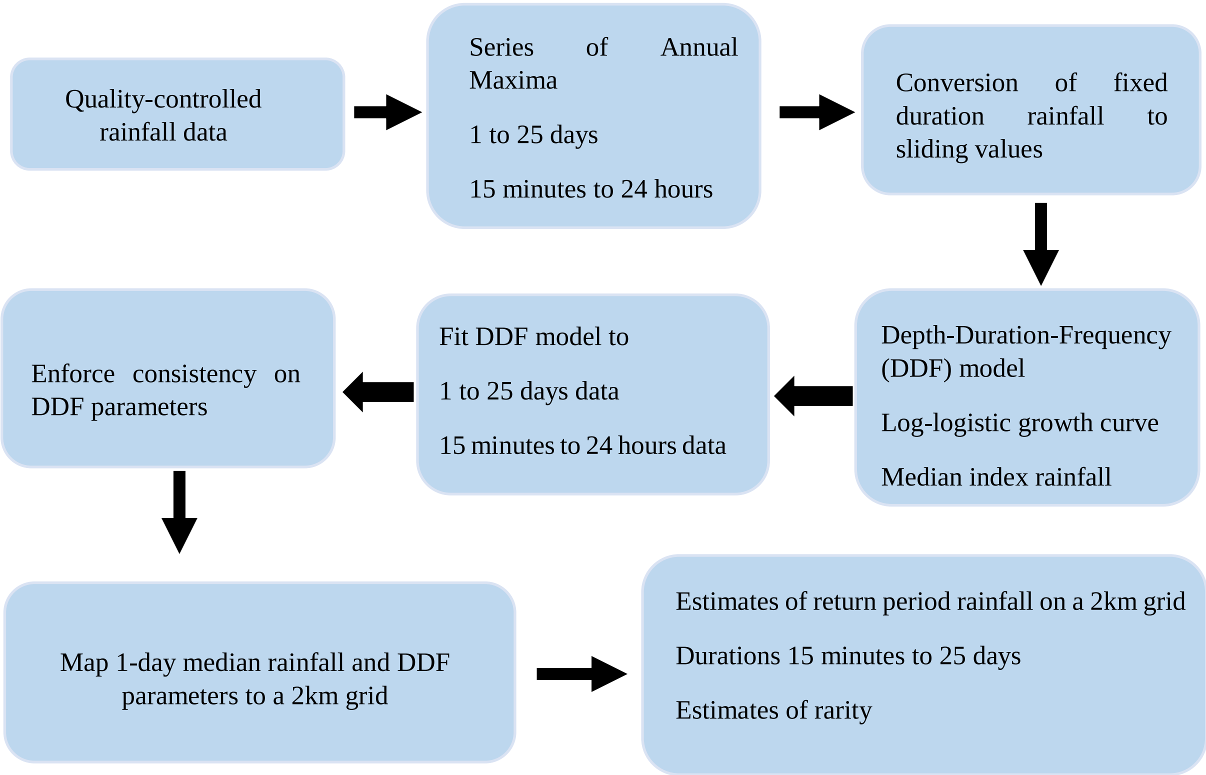

Figure 6: Workflow of the methodology employed in this study.

3.1. Conversion from fixed to sliding durations

A fixed-duration rainfall corresponds to the accumulation between fixed hours, which is the 24-hour total read at 0900UTC each day. A sliding duration rainfall consists of a rainfall total for a specific duration when the maxima is extracted from continuous records. The rainfall data available were the 1, 2, 3, 4, 6, 8, 10, 12, 16, 20 and 25-day annual maxima derived from daily totals read at 0900 UTC (Table 6). The objective was to estimate the 24, 48, 72, 96, 144, 192, 240, 288, 384, 480 and 600-hour return period rainfalls, where 24 hours is the annual maximum for any 24-hours period within the year. Achieving this from the 0900 – 0900 UTC data requires conversion factors from fixed to sliding durations.

At the 26 stations with both hourly and daily data, the log-logistic distribution was fitted to the 1, 2, 3, 4, 6, 8, 10, 12, 16, 20 and 25-day annual maxima of the 0900 – 0900 UTC rainfall totals and also to their 24, 48, 72, 96, 144, 192, 240, 288, 384, 480 and 600 clock-hour totals. Return period rainfalls of 2, 5, 10, 20, 50, 100 and 120 years were calculated for each, and the ratios were examined.

The mean of adjustment factors of fixed versus sliding durations for the various return periods is displayed in Table 7. Fitzgerald (2007) emphasised that since it is the index rainfall, the return values for the 2-year return period are the most important, although verifying how the factors vary with the increasing return periods is good. Therefore, it is useful to emphasise the difference in percentage between the mean of adjustment factors of fixed versus sliding durations for the various return periods obtained in this report and presented in Table 7.

Table 6: Annual maxima of the 0909 – 0900 UTC daily rainfall observations extracted for eleven thresholds ranging from 1 to 25 days.

Threshold											
Day	1	2	3	4	6	8	10	12	16	20	25
Hour	24	48	72	96	144	192	240	288	384	480	600

Table 7: Mean of adjustment factors of fixed versus sliding durations from 1 to 25 days for return periods (RP) ranging from 2 to 120 years.

Days	RP 2	RP 5	RP 10	RP20	RP 50	RP 100	RP 120
1	**1.157**	1.154	1.154	1.155	1.157	1.160	1.161
2	**1.071**	1.062	1.058	1.056	1.056	1.056	1.056
3	**1.049**	1.046	1.046	1.045	1.045	1.046	1.046
4	**1.038**	1.037	1.04	1.044	1.051	1.058	1.061
6	**1.030**	1.033	1.037	1.04	1.046	1.050	1.052
8	**1.030**	1.031	1.034	1.038	1.044	1.050	1.052
10	**1.021**	1.023	1.027	1.032	1.041	1.049	1.051
12	**1.017**	1.023	1.030	1.037	1.050	1.061	1.064
16	**1.015**	1.020	1.024	1.029	1.037	1.044	1.046
20	**1.012**	1.018	1.023	1.030	1.041	1.051	1.054
25	**1.012**	1.016	1.020	1.025	1.034	1.042	1.044

3.2. Depth-duration-frequency (DDF) model

A depth-duration-frequency (DDF) model is a method to estimate a rainfall amount as a function of duration and frequency, where the frequency is usually conveyed in terms of the return period. The DDF model described in detail in Fitzgerald (2007) has been used to calculate point rainfall frequencies over durations **D**, ranging from 15 minutes to 25 days and return periods, **T**, from 6 months up to 1,000 years for any location in Ireland using R software. This model consists of an index rainfall, the median of the annual daily maxima **R(2,1)** and a log-logistic growth curve which provides a multiplier of the index rainfall. R(2,1) is the 24-hour return period rainfall expected every 2 years; that is the annual maximum daily rainfall which has a 50% chance of occurring in any year.

The DDF model is based on a log-logistic growth curve with the predicted rainfall as a function of the median of the annual maxima R(2,1).

$$R(T,D) = R(2,1)\ D^{s}\ (T-1)^{c} \qquad \text{(Equation 1)}$$

R(T,D) is the predicted rainfall of duration D and return period T. The duration exponent **s** is the scale parameter, and the exponent **c** is the shape parameter. A detailed description of the model can be found in Fitzgerald (2007).

The extreme value theory that guides the Generalised Extreme Value (GEV) distributions requires assumptions such as stationarity (Coles, 2001; Tank *et al*., 2009) even though the climate is not stationary (IPCC, 2021). Although very long return values can be calculated, such as once in 1000-year levels from the fitted distribution, the confidence in such results may be minimal as the length of the return period is considerably greater than the period covered by the sample of extremes (Tank *et al*., 2009). Therefore, estimating return levels for very long return periods is susceptible to large sampling errors and possible large biases owing to imprecise comprehension of the shape of the tails of a distribution (Tank *et al*., 2009). In general, confidence in a return level diminishes quickly when the return period is more than twice the length of the original historical dataset (Tank *et al*., 2009). Therefore, in this research, return values are presented for return periods of 2, 5, 10, 20, 50, 100 and 120 years.

3.2.1. DDF model for durations from 1 to 25 days

The design rainfall outputs are produced for sliding durations from 1 day to 25 days. For instance, an 8-day estimate corresponds to 192 consecutive hours and may start at any hour of the day. This contrasts with the raw daily rainfall observation for a 24-hour period, defined for fixed durations, as the value read once daily at 0900 UTC.

The DDF model used for durations from 1 day (24 hours) to 25 days (600 hours) is given by,

$$R(T,D) = R(2,1)\ D^{e+f\ lnD}\ (T-1)^{a+b\ lnD} \qquad (\textit{Equation 2})$$

where the shape parameter **c** is given by ***a + b lnD*** and the scale parameter **s** is given by ***e + f lnD***. The additional *lnD* factors were introduced by Fitzgerald (2007) as it was found that there was a slow growth in the shape parameter with increasing duration and that adding the *lnD* factor to the scale improved the accuracy of the model. The scale parameter controls how spread out a distribution is. On a log-logistic distribution, the shape parameter determines the position of the peak probability and the skewness. The skewness constitutes a measure of the departure from the symmetry of a distribution.

The first step in determining the DDF model parameters is to extract the annual maxima of rainfall values for durations from 1 day to 25 days for each of the daily rainfall stations following a bock maxima approach (Coles, 2001). The annual maxima for daily stations are determined, with the rainfall year being from April to the following March.

These annual maxima are adjusted from daily to hourly equivalent values using the 2-year return period adjustment factors shown in Table 7 in section 3.1. The 2-year return period is equivalent to the median adjustment from a daily rainfall amount to an hourly equivalent duration rainfall amount. For example, converting a 3-day daily duration to a 72-hour sliding scale equivalent means multiplying the 3-day rainfall values by 1.049.

For each daily rainfall station, an L-moments approach (Hosking, 1990), also known as probability weighted moments, is used to estimate the shape of the probability distribution of the return period rainfall curve for each duration using the sliding scale adjusted annual maxima data. The L-moments method is preferred when samples are small (Tank *et al*., 2009). This probability distribution is then used to determine the return period rainfall from 2 years to 120 years for each duration. A matrix of the return period rainfall from 1 day to 25 days across all durations is constructed for each station.

The 4 DDF model parameters **a**, **b**, **e** and **f** from equation 2 are solved simultaneously for each station from its rainfall return period versus duration matrix.

To ensure consistency in the model output, that the return period rainfall should increase with increasing duration, a number of rules relating to the ratio of model parameters are applied,

$$e + 7b > 0\ ; \qquad a + 3.5b > 0 \qquad (\textit{Equation 3})$$

Further details are provided in Fitzgerald (2007).

Once the shape and scale parameters of the DDF model have been determined, equation 3 can be used to either calculate the return period rainfall at a given duration and return period; or, given a rainfall amount and duration, compute the expected return period.

The 4 DDF model parameters and the median rainfall amounts are interpolated across a 2km grid (Figures 7 – 9) using the methodology described in section 3.3. R software code can be used to calculate the 4 model parameters and median rainfall for any point, whether or not it is on the 2km grid, using an averaging algorithm which takes a weighted average of the nearest grid points. These model parameters allow the construction of a duration versus return period rainfall matrix to be calculated.

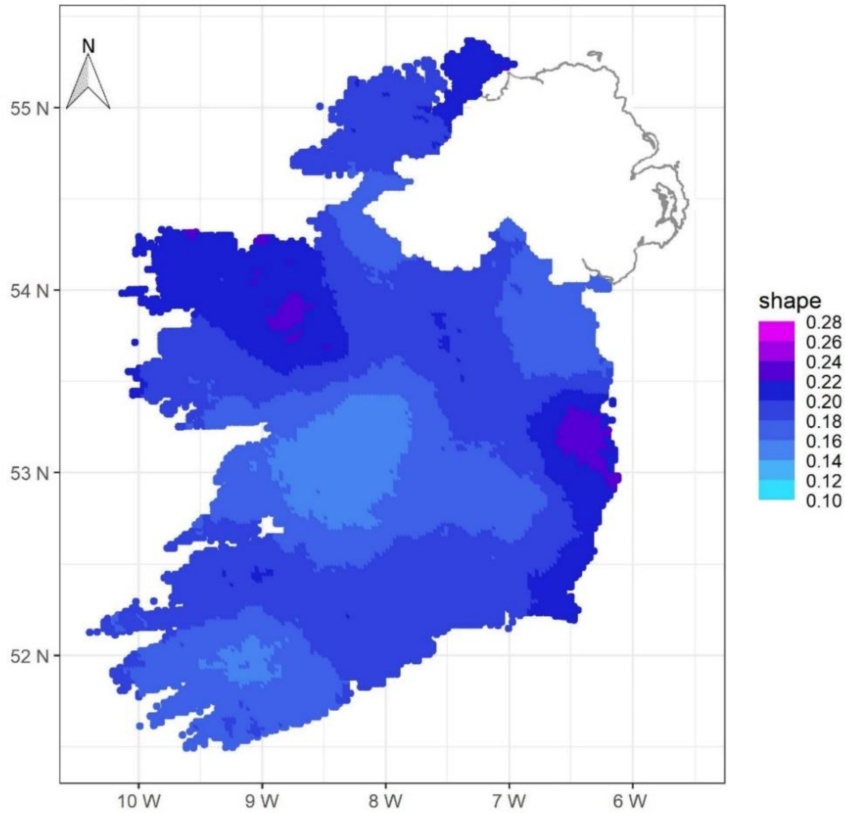

Figure 7: DDF model shape a.

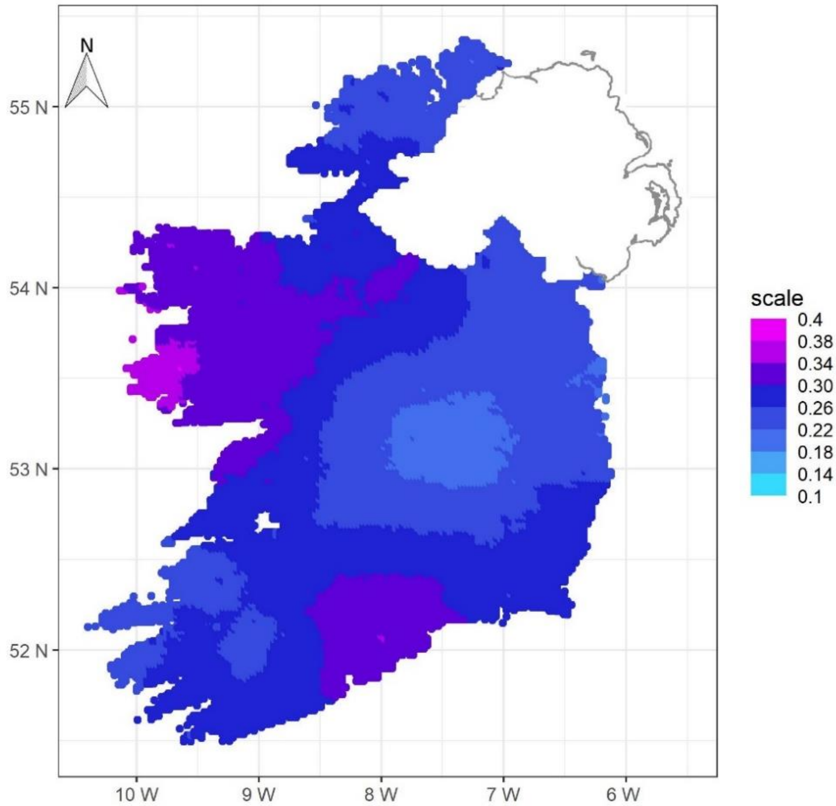

Figure 8: DDF model scale e.

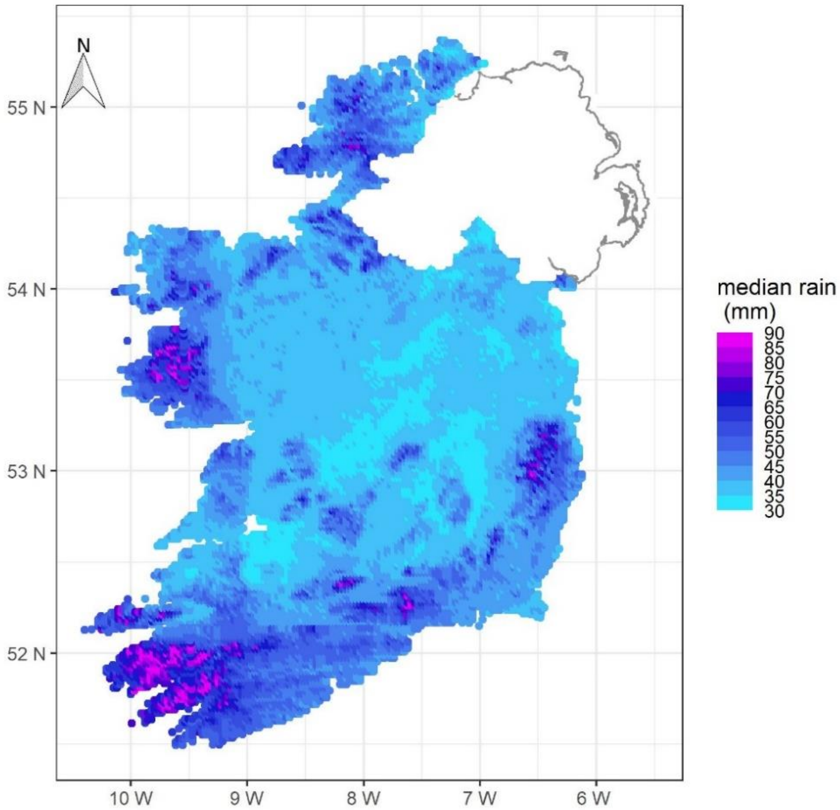

Figure 9: 24-hour median rainfall.

3.2.2. DDF model for durations from 15 minutes to 24 hours

The DDF model can be extended to durations below 24 hours down to 15 minutes following the methodology of Fitzgerald (2007). Here the return period rainfall model becomes,

$$R(T,D) = R(2,1)\ D^{s_{SD}}\ (T-1)^{a+h\ lnD} \qquad (\textit{Equation 4})$$

where the duration exponent $\mathbf{s_{SD}}$ is the sub-daily scale parameter, **a** is the same shape parameter used in the 1 day to 25 days model and a shape parameter **h,** which accounts for a slow change in return period rainfall as duration increases. The median of the annual daily maxima, R(2,1), is again used for the sub-daily model.

The structure of the sub-daily model ensures that at a 24 hours duration, where D = 1, both the daily and sub-daily models match.

A partitioned approach in designating the value of the sub-daily scale parameter, $\mathbf{s_{SD}}$, and the shape parameter **h**, based on the magnitude of the median of the annual daily maxima, was used. The values employed by Fitzgerald (2007) were tested by applying the short-duration (sub-daily) rainfall data as follows.

For each of the stations where short-duration rainfall data was available, the annual maxima across durations from 15 minutes to 24 hours were collated. From this data, an L-moments (PWM) methodology was used to determine the return period probability distribution and subsequently calculate a matrix of rainfall amounts at return periods from 2 years to 500 years and for each duration from 15 minutes to 24 hours.

The DDF model parameters are then determined for each station based on the return period versus duration matrix in a similar way to that used when the model parameters are derived for the 1 day to 25 days model described in section 3.2.1.

Rainfall amounts by return period and duration were calculated using a) the model using parameters derived from the short-duration rainfall station data and b) the partitioned values employed by Fitzgerald (2007). The rainfall values calculated using both methodologies were compared, and it was found good agreement between the two, with an RMSE of 6.5.

Thus, it was concluded that using the parameter values as defined in the previous version of the sub-daily model (Fitzgerald, 2007) was still appropriate for the latest version of the sub-daily model being developed here.

The sub-daily parameter values used are shown in Table 8.

Table 8: Sub-daily parameter values.

24 hour median	S_{SD}	Scale a	Shape h
24 hour median ≥ 60 mm	0.48	≥ 0.15	0
		< 0.15	-0.01
47 mm ≤ 24 hour median < 60 mm	0.43	≥ 0.16	0
		< 0.16	-0.015
35 mm ≤ 24 hour median < 47 mm	0.375	≥ 0.25	-0.01
		0.16 < **a** < 0.25	-0.015
		≤ 0.16	-0.023
24 hour median < 35 mm	0.33	≥ 0.25	-0.015
		0.16 < **a** < 0.25	-0.023
		≤ 0.16	-0.03

3.2.3. Average recurrence interval

The return period, T, is the inverse of the annual exceedance probability. For instance, the 2-year return period rainfall has an annual exceedance probability of 1/2 or 50%. The average recurrence interval (ARI) is the average interval between successive exceedances of a preset rainfall depth.

The Langbein formula provides a mechanism to compare the return period T and ARI measures of frequency.

$$\frac{1}{T} = 1 - \exp\left(-\frac{1}{ARI}\right) \qquad \textit{(Equation 5)}$$

This relationship allows the calculation of return period rainfall of 1 year and less,

ARI = 0.5 (twice per year frequency) T = 1.16
ARI = 1 (once per year frequency) T = 1.58

These values of return per T can be used in equation 5 to calculate the maximum rainfall by duration expected every 6 months and every year. Further details are provided by Fitzgerald (2007).

3.2.4. Implementing the DDF model

The DDF model (equation 2 for daily durations as in section 3.2.1 and equation 4 for sub-daily durations as in section 3.2.2) with defined scale and shape parameters and known median rainfall amount takes as its inputs the duration D and return period T. From this information, the rainfall amount at a given D and T and at a specific coordinate can be calculated.

The model also allows the return period T to be determined when the rainfall amount over a given duration is inputted. By way of illustration, a 28 mm rainfall amount recorded at a specific location and over a duration of 15 minutes is calculated to have a return period of 110 years.

Model parameters and median rainfall values based on daily rainfall station level data are interpolated across a 2km grid as described in section 3.3. However, R scripts allow the return period rainfall amount or return period in years to be determined at any grid point using an averaging of neighbouring 2km grid point model parameters.

3.3. Gridding

In order to produce a map based on a limited number of point sources of observations, here rainfall stations, the DDF model parameters and 24-hour median rainfall values need to be interpolated across the entirety of the grid to be mapped, a technique which is described as gridding. A 2km^2 grid covering the island of Ireland, which is based on the Irish National Grid (TM75 https://epsg.io/29903-1956), was employed.

The interpolation of 24-hour median rainfall values was carried out in two steps. First, a stepwise linear regression of the station rainfall amounts versus geographical variables at the observation points or weather stations was performed. These geographical variables include the stations' position (easting and northing, as coordinates of a location indicated as the distance eastwards and northwards, respectively, from a fixed datum) and elevation. However, other geographical parameters were found not strongly correlated and therefore not used ($R^2 < 0.1$).

A generalised example for median 24-hour rainfall of what the linear regression would look like is represented in equation 6:

$$r_p = r_{median\ 24hrs} + a_1 east + a_2 north + a_3 elevation + \boldsymbol{residual} \qquad (\textit{Equation 6})$$

where r_p is the predicted median 24-hour rainfall, $r_{median\ 24hrs}$ is the median 24-hour rainfall across all stations, *east*, *north* and *elevation* are the geographical variables used and $a_{1,2,3}$ are the values multiplying the geographical variables in order to get the best fit to the observation parameter, here 24-hour median rainfall. The regression is unlikely to be a perfect fit, and the $\boldsymbol{residual}$ quantifies the amount of the observation being predicted, which is not captured by the linear regression.

The second step interpolates the linear regression $\boldsymbol{residual}$ across grid points using a weighted average of the nearest stations to a particular grid point. A technique for interpolation of the residuals known as Inverse Distance Weighting (IDW) (e.g. Burrough *et al*., 2015) was applied by employing the R package gstat (Walsh, 2016).

The final grid point interpolation/prediction is based on equation 7:

$$r_p = r_{median\ 24hrs} + a_1 east + a_2 north + a_3 elevation + IDW(\boldsymbol{residual}) \qquad (\textit{Equation 7})$$

The described gridding methodology has been widely employed by Met Éireann, such as in generating official climate normals (e.g. Walsh, 2016) and other reports on the climate maps and data to support building design standards in Ireland (e.g. Mateus and Coonan, 2022a,b,c,d).

For the shape and scale parameters, it was found that there was no relationship between these factors and the geographical variables. Thus, the regression step was not used. Only the IDW was applied to interpolate model parameters across the grid. A similar conclusion was reached during the development of the DDF model described by Fitzgerald (2007).

3.4. Application for deriving rarity estimates

The maxima of all short-duration rainfall (sub-daily) observations attaining to or exceeding at least one of a set of thresholds for durations between 15 minutes and 24 hours were obtained from rain recorders of the Dines Tilting Syphon type, which were replaced at some stations in the mid-nineties by the tipping-bucket gauges. The Dines Tilting Syphon type has limitations in estimating extreme rainfall amounts of less than 15 minutes with sufficient accuracy (Logue, 1975). In addition, the 1-minute rainfall data are short-term series, with lengths ranging from 13 to 21 years in the period from 2002 to 2022, which does not allow the calculation of return values for various return periods for rainfall events with less than 15 minutes duration. Therefore, the estimation of return values for various return periods for rainfall events less than 15 minutes in duration should be considered as speculative; thus, the calculations were not attempted.

The DDF model can be applied reliably to rainfall durations from 15 minutes to 25 days, but estimates can be made at shorter durations.

As described in Appendix F of Fitzgerald (2007), an analytical solution to very short durations can be calculated using the formula,

Proportion of 15-minute rainfall = $D^{0.37515 - 0.0683\ln(D)}$, D = fraction of 15 minute duration (*Equation 8*)

For example, a 5-minute duration rainfall at a given return period is $(5/15)^{0.37515 - 0.0683\ln(5/15)} = 0.61$ of the 15-minute duration rainfall at that given return period.

An analysis of the 1-minute rainfall dataset in conjunction with the short-duration (sub-daily) rainfall data allows extrapolation of the 15-minute maximum rainfall amount to be made to shorter time periods. The average relationship between sub 15-minute rainfall amounts and the maximum falls 15-minute value is displayed in figure 10. This analysis shows that, on average, the 10-minute, 5-minute and 2-minute rainfall totals correspond with 0.83, 0.55 and 0.29, respectively, of the 15-minute rainfall amount (Table 9). This is in reasonable agreement with the output of equation 8 above.

For a specific return period, the maximum rate of runoff will result from an event in which the duration of the peak intensity is equal to the time of concentration, which corresponds to the minimum time for the whole area of a roof to contribute to the point the discharge where a time of concentration of 2 minutes is deemed representative for many roofs (BSI, 2007).

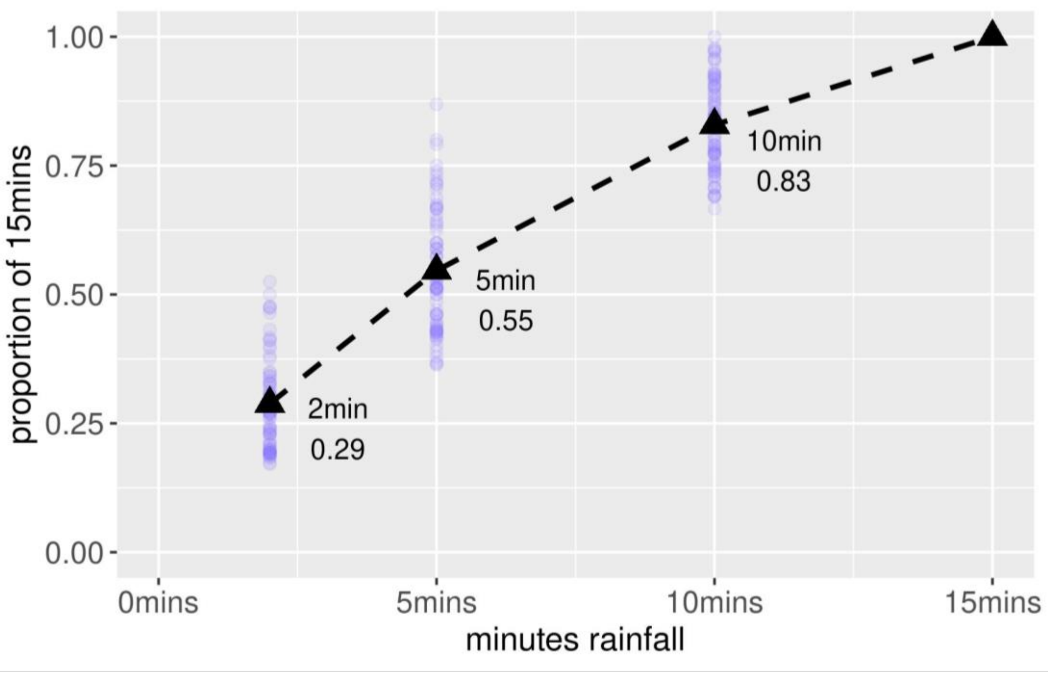

Figure 10: Proportion of the 15-minute rainfall distributed by the 10, 5 and 2 minutes duration rainfall in Ireland.

Table 9: Proportion of the 15-minute duration rainfall distributed by the 10, 5 and 2 minutes duration rainfall.

Duration	Equation (Fitzgerald, 2007)	Rainfall data
10 minutes	0.85	0.83
5 minutes	0.61	0.55
2 minutes	0.34	0.29

The most reasonable approach to estimating the sub 15-minute rainfall amounts is to determine the 15-minute duration rainfall at the particular return period and use the estimated proportions as shown in Table 9. As the DDF model is not designed to work at sub 15-minute durations, such short-duration rainfall amounts are not gridded.

4. Results

Return values for various return periods (2, 5, 10, 20, 50, 100 and 120 years) for specific rainfall thresholds ranging from 1 to 25 days (1, 2, 3, 4, 6, 8, 10, 12, 16, 20 and 25-day) and for 15 minutes to 24 hours (15 and 30 minutes and 1, 2, 3, 4, 6, 12 and 24h) were calculated and the results presented on a 2km grid for Ireland. For brevity, only the maps that referred to the return values 50, 100 and 120-year return periods for the 1-day rainfall duration are presented here (Figures 11 – 13). As an example, the return values of the various diverse return periods are presented for Cork Airport in Table 10. Regarding geographical patterns of rainfall intensities, greater intensities are seen along the northwest, west, southwest, south and southeast coasts and Wicklow for durations ranging from 1-day to 25-days.

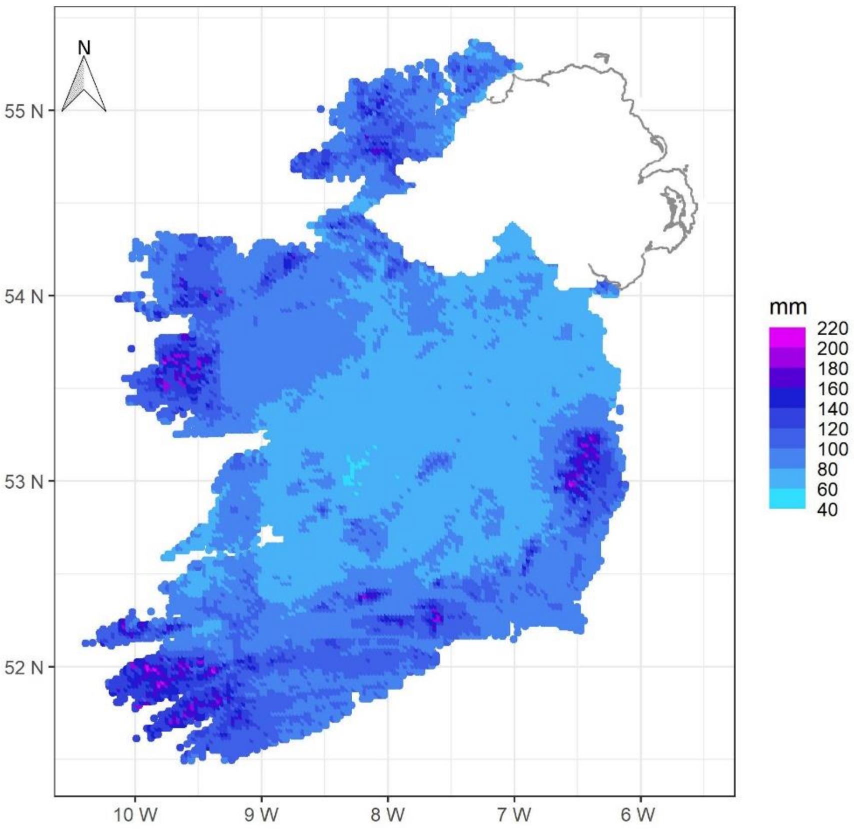

Figure 11: Return values for a 50-year return period for rainfall depths of 1-day duration in Ireland.

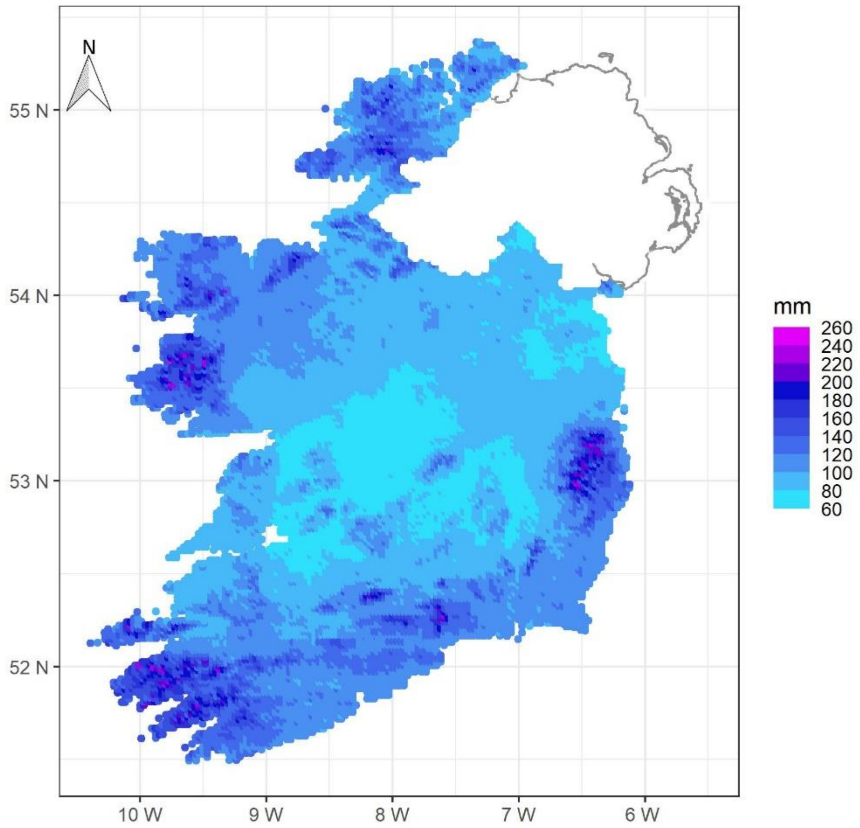

Figure 12: Return values for a 100-year return period for rainfall depths of 1-day duration in Ireland.

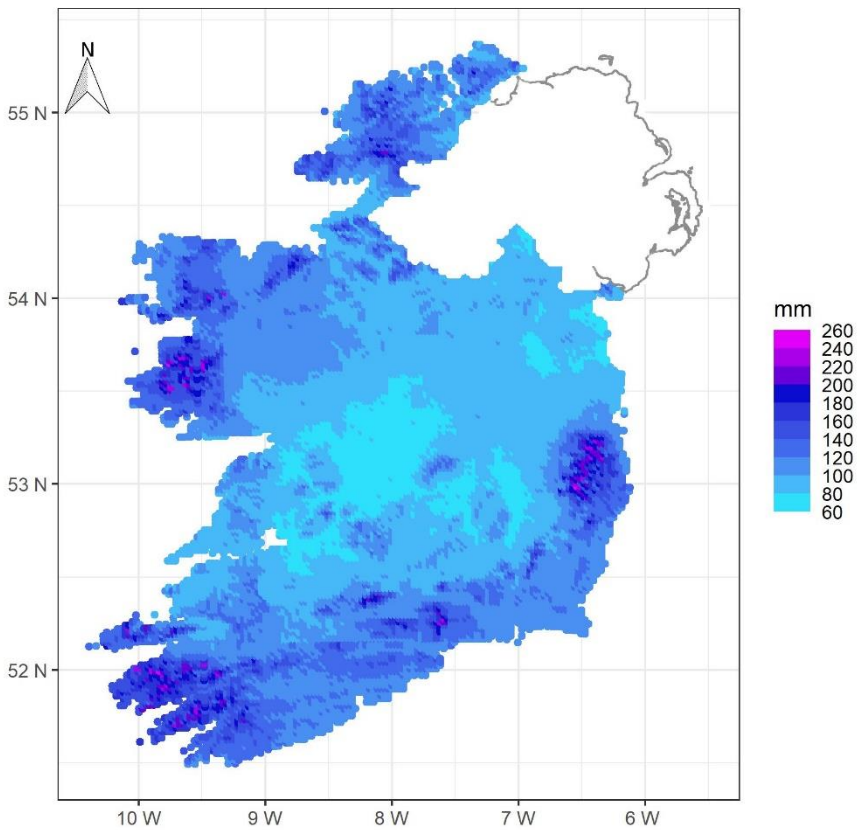

Figure 13: Return values for a 120-year return period for rainfall depths of 1-day duration in Ireland.

Table 10: Return values of rainfall intensities in mm with durations from 15 minutes to 25 days for various return periods in years for Cork Airport.

Duration	2yr	3yr	4yr	5yr	10yr	20yr	30yr	50yr	75yr	100yr	120yr
15 min	7.0	7.9	8.5	8.9	10.2	11.7	12.5	13.7	14.8	15.5	16.0
30 min	9.4	10.6	11.4	12.0	13.8	15.7	16.9	18.5	19.9	20.9	21.6
1 hr	12.7	14.3	15.4	16.1	18.6	21.2	22.8	24.9	26.8	28.2	29.1
2 hr	17.1	19.3	20.7	21.8	25.0	28.5	30.7	33.6	36.1	37.9	39.2
3 hr	20.4	23.0	24.6	25.9	29.8	33.9	36.5	40.0	43.0	45.2	46.6
6 hr	27.4	30.9	33.2	34.9	40.2	45.7	49.2	53.9	57.9	60.9	62.8
9 hr	32.7	36.8	39.5	41.5	47.8	54.4	58.6	64.1	68.9	72.5	74.8
12 hr	37.0	41.7	44.7	47.0	54.1	61.6	66.3	72.6	78.0	82.0	84.7
18 hr	44.0	49.6	53.2	56.0	64.4	73.3	78.9	86.4	92.8	97.6	100.8
1 day	49.8	56.2	60.3	63.3	72.9	83.0	89.3	97.8	105.0	110.5	114.1
2 days	64.1	71.6	76.4	80.0	91.0	102.4	109.6	119.1	127.2	133.2	137.2
3 days	75.7	84.0	89.3	93.3	105.4	118.0	125.8	136.1	144.8	151.3	155.6
4 days	85.9	94.9	100.7	104.9	18.0	131.5	139.8	150.8	160.1	167.0	171.5
6 days	103.7	113.9	120.4	125.2	139.9	154.9	164.1	176.3	186.5	194.0	198.9
8 days	119.5	130.8	137.9	143.1	159.1	175.4	185.3	198.5	209.4	217.5	222.8
10 days	134.0	146.2	153.8	159.5	176.6	194.0	204.7	218.6	230.3	238.8	244.4
12 days	147.5	160.6	168.7	174.8	192.9	211.4	222.6	237.3	249.5	258.6	264.4
16 days	172.8	187.3	196.3	203.0	223.0	243.2	255.5	271.5	284.8	294.6	301.0
20 days	196.2	212.0	221.8	229.0	250.7	272.5	285.6	302.8	317.1	327.5	334.3
25 days	223.7	240.9	251.5	259.4	282.9	306.4	320.6	339.1	354.4	365.6	372.8

5. Discussion

The DDF model described by Fitzgerald (2007) has been applied to generate the return values for various return periods ranging from 2 to 120 years and for specific rainfall thresholds ranging from 1 to 25 days and from 15 minutes to 24 hours. This research employed 728 stations in Ireland with quality-controlled daily rainfall total covering the period from 1941 to 2021 in the data analysis, with lengths ranging from 30 to 81 years. Additionally, 24 stations in Northern Ireland covering the period from 1853 to 2021 were used, with lengths from 30 to 169 years. A total of 38 sub-daily rainfall stations in Ireland with lengths ranging from 33 to 71 years in the period from 1946 to 2021 were used. For comparison, previous work by Fitzgerald (2007) used daily rainfall data for 474 stations in Ireland with an average period record of 41.2 years and a range of 20 to 64 years, and additional 103 stations from Northern Ireland. Regarding sub-daily rainfall, Fitzgerald (2007) employed 39 stations with lengths ranging from 15 to 55 years, although 37 stations had 30 or more years of record.

One of the consequences of climate change is the intensification of sub-daily rainfall extremes and prolonged periods of rainfall above average, which are associated with increased flooding (IPCC, 2021). In a warming climate, warmer air holds more water and consequently allows more moisture to rainfall events, resulting in an intensification of rainfall. The frequency and intensity of heavy rainfall events have increased since the second half of the 20th century (IPCC, 2021). A heavy 1-day rainfall event that occurred once in 10 years on average in the baseline period of 1850 – 1900 now likely occurs 1.3 times, and in the context of future global warming, it will likely occur at 1.5 times at 1.5°C, 1.7 times at 2.0°C and 2.7 times at 4°C warming level (IPCC, 2021). The annual number of wet days (> 20 mm of rain) is projected to increase by 10% and 14% mean values for the RCP4.5 and RCP8.5 scenarios, respectively, for the period 2041 – 2060 in Ireland. The annual number of very wet days (> 30mm of rain) is projected to increase by 21% and 31% mean values for the RCP4.5 and RCP8.5 scenarios, respectively, for the same period (Nolan and Flanagan, 2020). Given these climate change projections, the calculated return values are expected to change over time.

5. Conclusion

Return values for various return periods (2, 5, 10, 20, 50, 100 and 120 years) for specific rainfall thresholds ranging from 1 to 25 days (1, 2, 3, 4, 6, 8, 10, 12, 16, 20 and 25-day) and for 15 minutes to 24 hours (15 and 30 minutes and 1, 2, 3, 4, 6, 12 and 24h) were calculated according to the depth-duration-frequency model previously employed by Fitzgerald (2007) and the results presented on a 2km grid for Ireland. The outputs presented here will enhance resilience in support of climate change adaptation in Ireland.

This research supersedes the previous work of Fitzgerald (2007) and should be followed by decision-makers. It is hoped that the detailed explanation of the methodology and the rationale for the new maps being more accurate than the preceding maps provided here will assist regulators in adopting these new maps in their own jurisdictions. The results will also be of interest to a diversity of sectors, planners and policy makers to make long, lasting and climate sensitive decisions.

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