Deciphering extreme rainfall and historical floods at Easkey on the west coast of Ireland

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Introduction

Sometimes the traveller is confronted with accounts of rain that seem too large to be true. On the west coast of Ireland, a short day's cycling trip west of the rail head at Sligo, the beautiful village of Easkey sits beside a wooded fishing stream near the Atlantic coast (Figure 1). The stream rises at an elevation of 400–500m in the bog moorland of the Ox Mountains about 10km to the south and drains a scenic landscape of small pasture fields enclosed by dry-stone walls (Figure 2). The countryside has a timeless quality about it, but the many abandoned cottages that one sees along the coastal route suggest that there were significant land use and economic changes across the twentieth century. Surviving records reveal that the early nineteenth century agrarian population of the district was probably larger. The notion of a significantly higher population is supported by the ruins of a large Victorian workhouse further into the watershed at Dromor West. Wandering around the village of Easkey, one sees a beautiful nineteenth century church and a twelfth-century castle perched at the coastline with sweeping views of Sligo Bay. However, the attention of the weather observer is drawn to the tourist information plaque beside the bridge over the river on the approach to the village. The low level of the stream that one sees during typical summer-time conditions is in stark contrast to the accounts of the worst nineteenth century floods described on the sign:

> *The structure we see today replaced a wooden bridge that was washed away after it had rained for 40 days in 1844 … The new bridge was completed in 1847, known as 'Black Forty-Seven', as it was the worst year of The Potato Famine … This Easkey bridge withstood the great flood-thunder burst on 1877, when the waters rose 10 feet above the centre arch, and all of the village and the fields around were flooded, but the bridge stood sound, a testimony to the quality of the workmanship.*

For the visiting weather observer, the text sparks several questions. What kind of rain generating conditions occurred to make the stream flood like this? Is it possible to find meteorological measurements from weather stations so far back in time to corroborate the written account? If so, is it possible to determine the day or at least the month of these two contrasting rain events? Because any surviving weather records would likely be at some distance from Easkey, more general questions arise about typical spatial footprints of extreme rainfall events in Ireland, and the influence of topography in augmenting rainfall accumulations. It is striking that these events took place over 150 years ago, with no repeat occurrence in the twentieth century or the first quarter of this century when weather extremes from recent climate change are being reported in the media. Was there something notable about the weather conditions in the nineteenth century that has no analogue now? Finally, what is the implication of extreme rainfalls like this on engineered hydrological structures?

Figure 1. Sketch of the stream valley of Easkey, looking upstream towards the bridge on the left (after a tourist photo on the Easkey Community Council website https://www.boardmatch.ie/not-for-profit/easkey-community-council-clg).

Learning from contemporary precipitation datasets 1941–2014

To begin the analysis of the Easkey floods, modern datasets can be queried to understand the characteristics of extreme precipitation features on the island. Data from the contemporary gauge network in Ireland give information about extreme precipitation events and also the month when they occur. Met Éireann has produced 1km gridded fields of daily precipitation from 1941 to 2014 using an interpolation of a dense network of rain gauges across the country (Walsh, 2016). The dataset was processed to derive maps of the annual maximum daily rainfall for each grid cell, together with its date of occurrence. To quantify rainfall extremes, a return period metric is often used, or the rainfall total that can be expected over the return period of say 20 years. Here, the Gumbel method was used to obtain the rainfall total associated with 20-year

RMetS Royal Meteorological Society

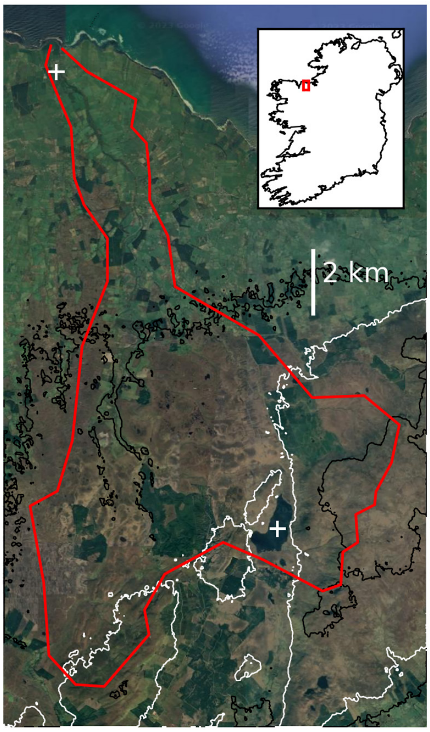

Figure 2. Map of the Easkey Stream catchment (red outline) with the inset map showing the site location in northwest Ireland. The background photograph is a Google Earth screen capture showing a visible image of the land cover (mostly enclosed pasture fields with some patches of forest and upland blanket bog moorland in high elevation areas to the south) at approximately 21m pixel resolution. The qualitative assessment from the visible image is corroborated by the CORINE land cover product. Three contours are shown (100m in black, 200m in white and 400m in black) from the high-resolution (30m) ASTER elevation dataset. The highest point of the watershed is about 500m in the Ox Mountains in the southeastern part of the image. White crosses mark the bridge in Easkey village (top) and a large lake in the upper part of the watershed in the Ox Mountains (bottom). The catchment groundwater and soil characteristics are described in the Geological Survey of Ireland (2023) online report. The Internet source websites for the spatial information in the figure are given in the Acknowledgements.

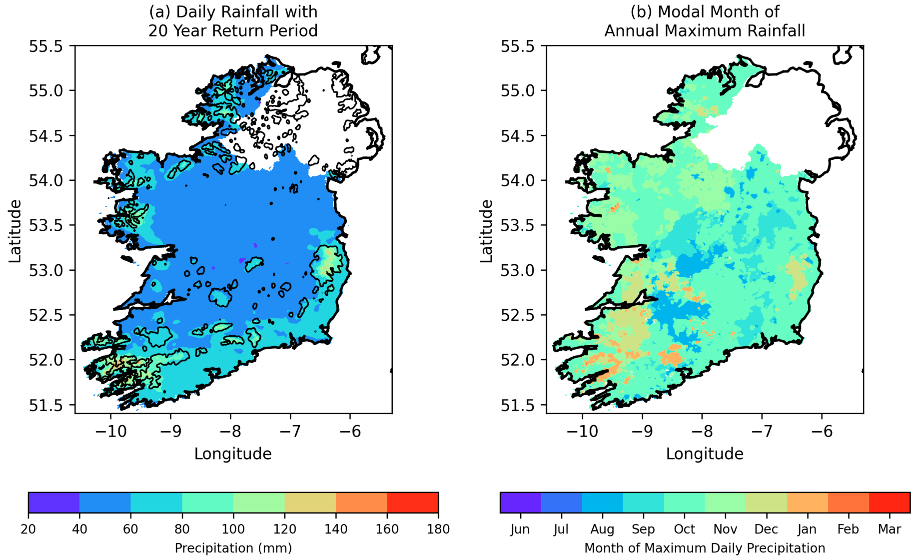

Figure 3. (a) Daily rainfall accumulation with a 20-year return period highlighting the highest accumulations in mountain areas, (b) modal month of occurrence of the highest daily rainfall of the year in the period 1941–2014. Black lines in (a) show the 200m elevation contour from the GTOPO30 (2018) ~1km resolution topographic dataset.

return period (Logue, 1975; Fitzgerald, 2007; Ahilan *et al*., 2012). The result is shown in Figure 3(a) and highlights that an annual maximum daily rainfall accumulation in the range 40–60mm can be expected for most of the island for this level of extreme event. However, for coastal areas and particularly mountain areas much greater daily accumulations can be expected.

Maps were also queried to find the most likely month of occurrence of the annual maximum daily rainfall. A histogram was created of the month of maximum rainfall for each gridded rainfall pixel, and the mode of the distribution was taken to create a map indicating the month of occurrence of the annual maximum (Figure 3b). For cases where two or more months have the same modal value, all occurrences were retained, and the value chosen for the map was selected by comparison with the surrounding cells. The result in Figure 3(b) indicates that the most common months for the occurrence of the annual maximum rainfall are October and November, with September and December representing smaller areas. For the 74-year gridded data record, no modal maxima occurred in April or May. The Easkey floods therefore most likely occurred between August and December, with October and November having the highest probability.

Some nineteenth century weather station data are available to assist the interpretation, but they are at varying distances from Easkey. Therefore, it is important to understand the spatial coverage of rainfall extremes in Ireland to assess how representative distant stations might be. Three extreme events were chosen to illustrate the spatial extent or footprint of notable extremes, including (i) the highest daily rainfall accumulation in the 74-year gridded dataset (recorded for a mountain location in southwest Ireland with 241mm of rainfall on 18 September 1993), (ii) the highest daily total for central Dublin (83.2mm on 24 October 2011) and (iii) the highest daily rainfall for the town of Sligo (69.8mm on 15 August 1970). These cases were chosen to highlight the general characteristics of the dataset, with the selected points illustrating characteristics for the main east, southwest and northwest sections of the island. Note that for the case of Dublin, there was an extreme rainfall event on 11 June 1963 with a greater daily rainfall amount, but this was not effectively captured by the official rain gauge network, and it is discussed further below. It is significant that the dates are all different. There has never been a year in the Met Éireann dataset when the date of the largest rainfall accumulation for the three locations was the same. Typically for a given year, there is a list of several dozen dates for the maximum rainfall in Ireland, depending on the location. No single weather system has been so extensive and powerful that the date of maximum rainfall is the same everywhere in Ireland.

Maps of annual maximum rainfall for the three case events were queried to identify the spatial footprint with same date of maximum annual rainfall (Figure 4). The rainfall footprints for the southwest event (Figure 4a) and Dublin (Figure 4b) were limited in extent. However, the Sligo event was part of a wide swath that stretched across to Dublin (Figure 4c).

The Easkey nineteenth century floods

Original meteorological measurement records are available to gain insight into the 1844 and 1877 Easkey floods. There are more records available for 1877 (Keane, 2017), and some are associated with a network of meteorological measurements across the United Kingdom (UK) that commence in the 1850s with the establishment of the UK Meteorological Office. For 1844, the measurement network is much sparser (Hawkins *et al*., 2022), but there are some monthly precipitation measurements in this early period before telegraph communications and railway transport links were established in Ireland.

To corroborate the 1877 Easkey flood and determine a likely date of the event, the archive of daily rainfall compiled by Ryan *et al*. (2021) was queried for stations operating in 1877. Daily data for all stations were extracted, and the annual maxi-

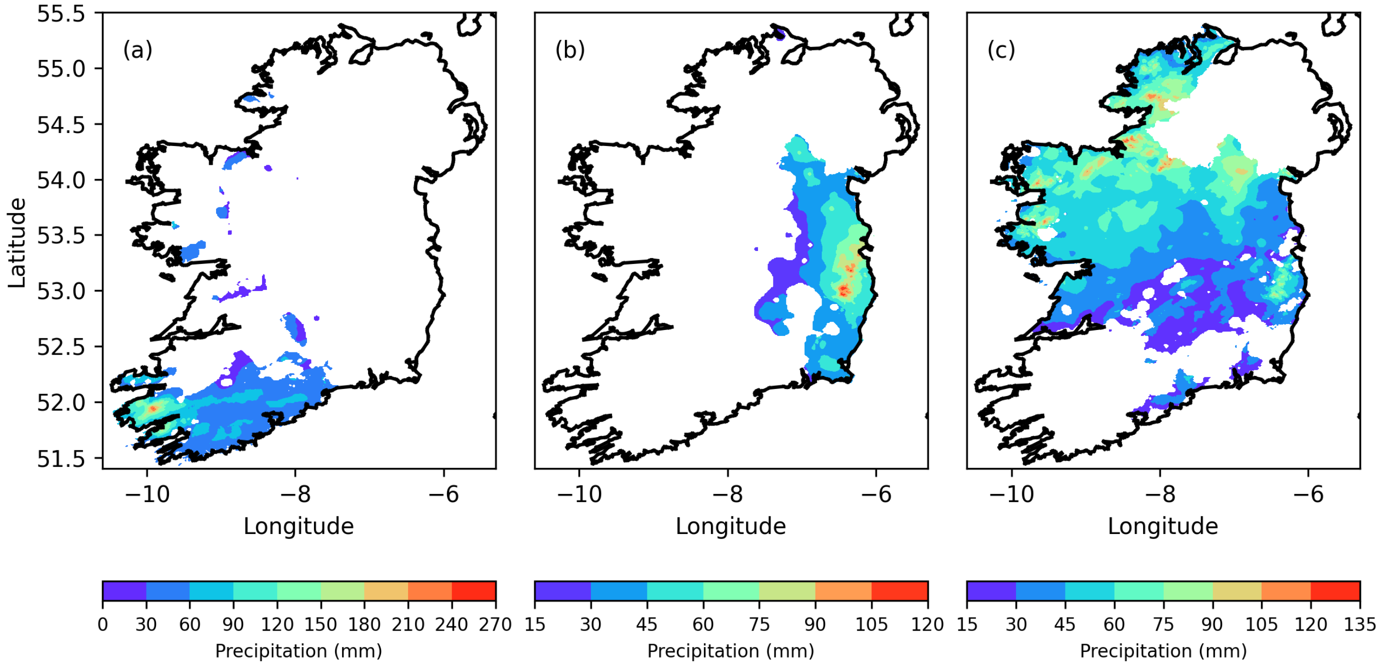

Figure 4. Daily rainfall accumulations for the wettest day of the year where the specified date is (a) 18 September 1993 (date of the maximum Ireland daily accumulation in the period 1941–2014, recorded in the southwest), (b) 24 October 2011 (date of highest rainfall at Dublin Airport in the period 1941–2014) and (c) 15 August 1970 (date of the highest rainfall in the town of Sligo in the period 1941–2014).

mum value identified. These are plotted in Figure 5, together with the associated date. Unexpectedly, it was difficult to identify consistency in the dates of the maximum daily rainfall with each station registering a unique date with the months April to November, plus January, represented. The two stations nearest Easkey have two dates in October for the maximum rainfall: Enniscoe with 26 October 1877 and Markree Observatory with 14 October 1877. Time series of daily rainfall in 1877 for the Markree Observatory and Enniscoe are shown in Figures 6(a) and (b), and reveal that there were several days during the year when there were comparable maximum values. While the highest daily rainfall for each station was registered in October, comparable levels fell on 2 days in August and 1 day in June for the Markree Observatory (Figure 6a) and in January, August and December for Enniscoe (Figure 6b). The high rainfall of 91.4mm at Greenore on the eastern side of Ireland on 31 May 1877 raised the possibility that the Easkey flood may have been linked with a snowpack melt episode in late spring, but the minimum and maximum temperatures from the Markree Observatory (Figure 6a) were high throughout the year, and there were no extended freezing intervals.

The problem of identifying the day of the event is helped by documentary accounts of regional flooding events during the year. For example, there were severe floods across Scotland on 14/15 October 1877 (McConnell, 1997). This supports the hypothesis that the Easkey flood may have occurred about the same time, especially since it agrees with the date of the annual maximum rainfall for the Markree Observatory. However, stronger evidence is presented in the newspaper account of the remarkable flood in Ballina on 18 August 1877 that was due to an isolated thunderstorm extending a few tens of kilometres eastward to the Ox Mountains in the direction of Easkey (Ballinrobe Chronicle, 1877). Markree Observatory was outside the main region of impact, but it did register high relative humidity on the morning before the thunderburst that was also noted in the media account, and there was a small amount of rain. Enniscoe, which is just to the west of Ballina, was also outside the main region of impact, but it nevertheless registered a significant amount of rainfall, and the accumulation on 18 August 1877 was the fourth highest of the year (Figure 6b). Some support for the correct date of the Easkey rain event comes from the results of the most recent version of Twentieth Century Reanalysis Project (Slivinski *et al*., 2021), presenting integrated rainfall totals over 1-degree pixels. Analysing daily rainfall totals for the Easkey region for August and October 1877 (Figures S1–S8), the highest daily rainfall is registered for 13 October 1877, although 18 August 1877 is a strong candidate day for the 2 months of data considered and is still the favoured choice for the Easkey flood date. A great advantage of the Reanalysis Project is that it gives an overview of the regional rainfall situation on 18 August 1877, which is revealed as a large rainfall band over western Ireland extending westward and southward over the Atlantic Ocean. Interestingly, the original daily Met Office weather maps compiled from 50 telegraphed reports sent to London from around western Europe (Meteorological Office, 1877) give little indication of the high rainfall events that were causing flooding problems in Scotland and Ireland in August and October 1877. Still, the weather situation maps for western Europe give useful background information for what was happening in Ireland on 18 August 1877. The maps indicate gentle surface winds from the south and no large decreases in barometric pressure. Combining all information, a picture emerges that the 1877 Easkey flood was likely due to an isolated convective thunderstorm embedded within a larger rain system.

To understand the 1844 event, the monthly rainfall records rescued by Hawkins *et al*. (2022) were consulted. The monthly timescale of the measurement record in this case approximately matches the source report that flooding had resulted after 40 days of rain. The number of available stations in 1844 is smaller than in 1877 with only about ten time series datasets available in Ireland (Figure 7a). Markree Observatory was registering rainfall data during 1844 and is the station closest to Easkey. A time series of the monthly data for Markree Observatory for 1844 is shown in Figure 7(b). This reveals a prominent peak in October 1844, which most likely corresponds with the earlier Easkey flood account. Contemporary newspaper articles also mention severe floods in different parts of Ireland on different dates in September to November, and from the descriptions, the floods are mostly due short intense rain episodes. Additional information for

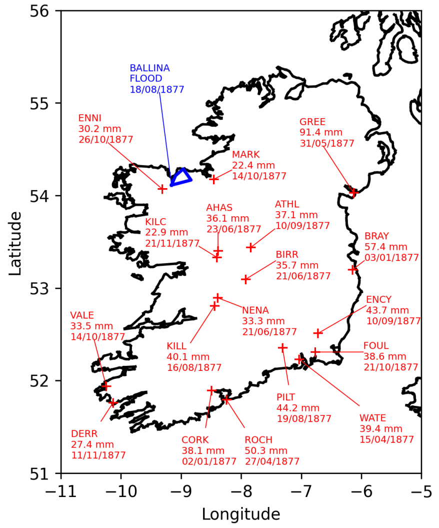

Figure 5. Annual maximum daily rainfall for available Ireland stations in 1877, with date indicated. The stations are abbreviated by the first four letters of their full name except where otherwise noted: Ahascragh, Athlone, Birr Castle, Bray, Derrynane Abbey, Enniscoe, Enniscorthy (ENCY), Foulkesmill, Greenore, Kilconnel Rectory, Killaloe, Markree Castle, Nenagh, Nuig, Piltown, Queens College Cork (CORK), Roches Point, Valentia and Waterford. The blue polygon shows the approximate spatial extent of the thunderstorm that caused serious flooding in Ballina (a town 20km southwest of Easkey) on 18 August 1877.

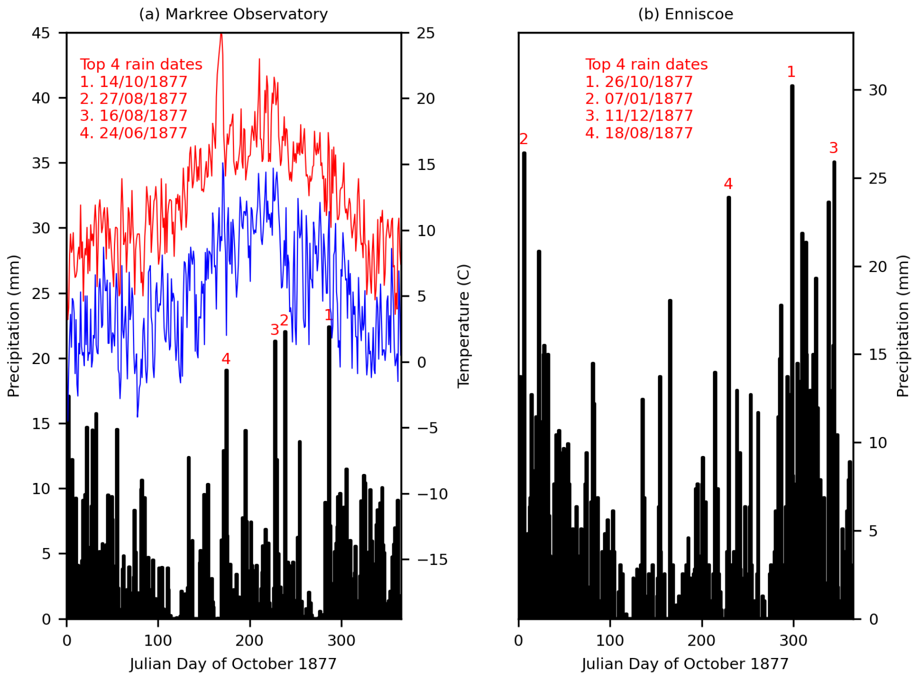

Figure 6. Time series of (a) daily rainfall (black) and the minimum (blue) and maximum (red) temperature for Markree Observatory in 1877 and (b) daily rainfall for Enniscoe in 1877. For each station, the 4 wettest days of the year are identified and the dates printed. For Markree Observatory, a red dashed line marks 18 August 1877 when there was a severe flood at Ballina, 20km southwest of Easkey.

the intense rain events is presented in the caption for Figure 7. The newspaper information is important because the ~170mm of rainfall in October 1844, though high, was not exceptional in the full 107-year record for Markree Observatory. The rainfall peak in October 1844 was met or exceeded 50 times in the full Markree Observatory record of 1272 months, so that the return period of a comparable or worse wet month is about 2 years. By contrast, the information on the plaque in the village beside the stream indicates only two remarkable flood events. It is possible that there was rain throughout October 1844 leading to saturated catchment conditions with the remarkable flood arising due to an intense short-lived rain episode in the small watershed, similar what happened in 1877. The results of the Twentieth Century Reanalysis Project (Slivinski *et al.*, 2021) support this view with predicted rainfall accumulations for all days in October 1844 and a large rainfall on 8 October 1844 that is 2–3 times higher than the average daily accumulation of the month (Figures S9–S12). The most likely day of the 1844 Easkey flood is therefore 8 October 1844. The result highlights the remarkable strength of the Twentieth Century Reanalysis Project—constrained only by a very sparse network of daily surface atmospheric pressure measurements—to deliver important meteorological information for remote regions in the distant past.

Discussion

A chance encounter with a roadside plaque has prompted an investigation into the temporal and spatial characteristics of precipitation extremes in Ireland. Although the available evidence suggests that the two extreme floods in Easkey occurred during the month of October in 1844 and in August 1877, respectively, information from the nearby meteorological station at Markree Observatory does not neatly match the flood description. In both instances, the rainfall totals reported at Markree seem too low to account for the flood events at Easkey. For the October 1844 event, a closer investigation of the Markree data indicates that tens of comparable flood events would have been expected at Easkey during the nineteenth and early twentieth centuries, instead of just the two reported. On the other hand, newspaper accounts from other parts of Ireland in 1844 indicate brief flood events following intense rainfall, so Easkey may have had a particularly strong rain episode on top of a generally wet month. For the August 1877 flood, there is a poor match with the available quantitative records and the strongest corroborating evidence comes from an incredible flood account from the nearby town of Ballina.

In both cases, the issue may have been pronounced spatial inhomogeneities between Easkey and Markree. Easkey is at a more exposed location on the coast, and its watershed includes the slope of a 400m mountain ridge to the south. Rainfall in Ireland tends to be higher in mountain areas, and there may have been orographic enhancement at Easkey. In addition, some of the nineteenth century floods may have been linked with atmospheric rivers: filaments of moisture-rich air that track polewards from subtropical source regions causing intense precipitation events in localised areas where they make landfall, especially where the moist air mass is forced over topography. The atmospheric river phenomenon was described relatively recently in the 1970s, and the advent of satellites imaging of total column water vapour (particularly the Special Microwave Imager SSM/I) has provided an unambiguous view of the phenomenon (Ralph and Dettinger, 2011; Lavers and Villarini, 2013). In a series of publications starting from the 1990s, atmospheric river contributions to extreme precipitation events have been identified on the west coast of North America, South America and western Europe (Lavers and Villarini, 2013). For Ireland, atmospheric rivers have been linked to many extreme precipitation events in the southwest and northwest (Woods, 2019). However, atmospheric rivers tend to have a larger impact area, affecting a length of coastline >100km when they reach land. They are also linked with strong lower troposphere winds (Matthews *et al.*, 2018). This was not the situation for the Easkey flood August 1877, which was likely due to an isolated thunderstorm.

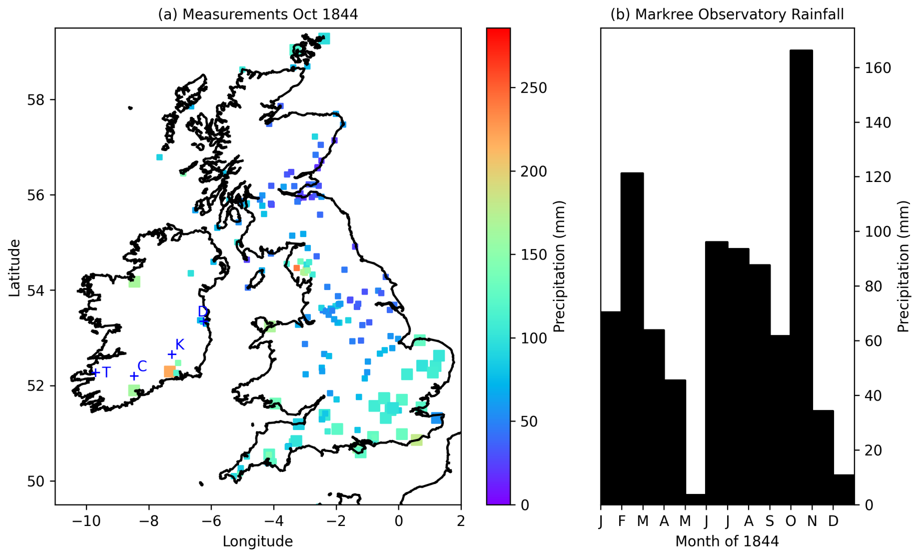

Figure 7. (a) Map of maximum monthly precipitation from measurements across the British and Irish Isles with events in October plotted with oversized symbols. Newspaper accounts of extreme weather in Ireland is denoted by letters. 'C' is an account of flooding at Castletownroche in the days before 16 October 1844 (Kerry Evening Post, 16 October 1844b). 'D' is an account of a storm surge and rain flooding in Dublin associated with a severe southeast storm on 8–10 October 1844 (Kerry Evening Post, 12 October 1844a). 'K' is an account of flooding in Kilkenny on 3 November 1844 (Kilkenny Evening Post, 9 November 1844). 'T' is an account of flooding in Tralee on 14 September 1844, with an additional flood earlier in the year on 23 February 1844, followed by a 'hurricane' on 25 February 1844 (Kerry Examiner, 27 February 1844). (b) Time series of monthly rainfall for Markree Observatory for 1844.

There may have also been factors that contributed to the Easkey floods in the nineteenth century that have not been at play since. The structure of the economy and society of Ireland was different from the present period, with a significantly higher rural population engaged in subsistence agriculture. This may have had an impact on land use and the potential landscape response to large rainfall events. The nineteenth century marks the end of the Little Ice Age, a European climate anomaly that started in late medieval times and was characterised by lower temperatures than during the twentieth century. European literature accounts from the period indicate the occurrence of extratropical winter storms of unusual severity with no analogue in the recent period. Reistad *et al*. (2005) clarify that the reason may have been linked with the lower sea-surface temperatures between the Faroe Islands and Iceland leading to high atmospheric meridional temperature gradients at these latitudes and enhanced cyclone formation. The year 1877 was additionally unusual because it was the middle of the worst El Niño episode of the last 800 years (Singh *et al*., 2018). Although the El Niño episodes of 1982–1983, 1997–1998 and 2014–2016 were the strongest in living memory, the El Niño of 1876–1878 was a millennial scale event that was worse for its impacts (Singh *et al*., 2018[1]). There was a global pattern of temperature and precipitation anomalies that resulted in droughts and famines in large areas of different continents and southeastern Asia in particular. The impact of El Niño events in the North Atlantic and European region is debated, but the review of Brönniman (2007) presents evidence that they are linked with positive precipitation anomalies in western Europe. Emerton *et al*. (2017) indicate a link between El Niño and river floods in northwestern Europe, but only during the declining phase of an El Niño, or the interval December–August 1878 for the present Easkey flood study. For the evolving phase of an El Niño (or 1876–1877), the link between the El Niño and river flow extremes in Europe is much weaker.

Although the surviving nineteenth century information is not very good at quantifying the amount of rain that fell during these events at Easkey, it is important to know that they occurred and were comparable to the worst documented events in the British and Irish Isles (Clark and Dent, 2021). The worst-case rainstorms are used by reservoir engineers to design structures that maintain their integrity during unexpected extreme events. Extreme rainstorm case studies across a region are used to create assessments of probable maximum precipitation, or the physical limit of 24h precipitation. For most of the British and Irish Isles, this value is approximately 400mm, varying up to about 600mm in mountainous regions (Clark and Dent, 2021). This seems like an astonishingly large number given that the largest daily rainfall in the Dublin city area in the Met Éireann gridded fields is just over 80mm. On the other hand, there was an unusual localised intense rainstorm in southside Dublin on 11 June 1963 where unofficial rain records gathered from amateur weather observers indicate that the maximum measured rain accumulations were 240mm or more (Clark, 2019). Associated media accounts of the event indicate an astonishing amount of water that are comparable with the historical accounts from Easkey and Ballina from the nineteenth century. The worst event for the UK was the Martinstown, Dorset storm of 18 July 1955 with a maximum measured accumulation of 355mm, again with almost unbelievable media accounts (Clark, 2006). As high as the rainfall accumulation seems, the rainstorm could have been worse, and reservoir hydrologists who calculate probable maximum precipitation also take into account what would have happened if the atmospheric moisture content had also been at its worst-case level. Applying the probable maximum precipitation estimate of 400mm in 24h to the Easkey river catchment area of 98km^2 gives an approximate discharge rate of about 454m^{3}s^{-1} past the bridge. This is about four times higher than the average flow of the Severn River in the UK or about 50% more than the average flow of the River Shannon in Ireland. The information plaque beside the river gives the approximate height of the flood waters that would have built up behind the bridge during the 1877 flood so that survey information of the bridge dimensions could be used to roughly calculate the flow through the submerged arches and over the top of the bridge parapet.

Understanding plausible maximum floods is important for risk management and can assist in flood planning under current and future climate. However, as we show here, this is a particularly challenging task for small, flashy catchments where large floods can be generated from rainfall events with a small spatial signature. Historical weather records and newspaper archives can assist in evaluating the timing and magnitude of past flood events. Recent research in rescuing paper-based rainfall records and quality assuring resultant time series have added considerable potential for contextualising historical extremes (e.g. Noone *et al*., 2016; Ryan *et al*., 2021; Hawkins *et al*., 2022). However, additional paper-based records, especially for daily precipitation, remain to rescued and would add considerably to our understanding of the magnitude and spatial variability of historical extremes (Mateus, 2021). Likewise, the Twentieth Century Reanalysis Project (Slivinski *et al*., 2021) has demonstrated great value in identifying the date of extreme rainfall events in the distant past, based mostly on a sparse network of atmospheric pressure meas-

[1]https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

urements to constrain a weather prediction model. Similarly, historical newspaper records hold much potential for verifying historical meteorological observations and understanding the impacts and extent of past extremes. Previous research has shown how such documentary sources can be used to develop impact databases for drought events (O'Connor *et al.*, 2022; Jobbová *et al.*, 2023), verifying meteorological records (Noone *et al.*, 2017) and exploring the cultural significance of past extreme weather events (Murphy *et al.*, 2017). Ireland has among the longest continuous newspaper records in the world and future research could leverage this to develop a catalogue of major flood events reported on the island. Haigh *et al.* (2017) demonstrate the development and utility of such a dataset for coastal flooding in the UK.

Finally, while the flood events of interest date from the nineteenth century, climate change is likely to significantly alter flood risk into the future. Recent research has shown that observed increases in annual rainfall totals for northwest Ireland have emerged as unfamiliar relative to early industrial conditions, while increases in rainfall intensity across the island are consistent with expectations from the Clausius–Clapeyron relationship, with an average increase across stations of approximately 8% per degree warning (Murphy *et al.*, 2023a). With continued climate change, increases in flood magnitude are expected over the coming decades (Murphy *et al.*, 2023b), emphasising the importance of better understanding plausible maximum extremes from the historical record.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure S1. Daily rainfall totals for each of the days of August 1877. Note that the colour scales in the graphs are individually normalised so that the same colours do not represent the same rainfall accumulations for all graphs. The rainbow colour scheme shows high rainfall in red and low (or no) rainfall in blue.

Figure S2. Daily rainfall total (in kgm^{-2}) across Europe for 18 August 1877 with colour scale key presented.

Figure S3. Daily rainfall totals for each of the days of August 1877.

Figure S4. Latitude and longitude sections of daily rainfall amounts for 18 August 1877 through the Easkey pixel of the Europe map.

Figure S5. Daily rainfall totals for each of the days of October 1877. Note that the colour scales in the graphs are individually normalised so that the same colours do not represent the same rainfall accumulations for all graphs. The rainbow colour scale shows high rainfall in red and low (or no) rainfall in blue.

Figure S6. Daily rainfall total (in kgm^{-2}) across Europe for 13 October 1877 with colour scale key presented.

Figure S7. Daily rainfall totals for each of the days of October 1877.

Figure S8. Latitude and longitude sections of daily rainfall amounts for 13 October 1877 through the Easkey pixel of the Europe map.

Figure S9. Daily rainfall totals for each of the days of October 1844. Note that the colour scales in the graphs are individually normalised so that the same colours do not represent the same rainfall accumulations for all graphs. The rainbow colour scale shows high rainfall in red and low (or no) rainfall in blue.

Figure S10. Daily rainfall total (in kgm^{-2}) across Europe for 8 October 1844 with colour scale key presented.

Figure S11. Daily rainfall totals for each of the days of October 1844.

Figure S12. Latitude and longitude sections of daily rainfall amounts for 8 October 1844 through the Easkey pixel of the Europe map.

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