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2000 - 2017 inventory of extreme weather events in Ireland

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Declaration

I, Adam Pasik, certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or tertiary institution and to the best of my knowledge, contains no material previously published or written by another person, except where due reference has been made in the text.

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Abstract

Globally, extreme weather events are responsible for far more financial losses than the increase in mean temperature. In the context of climate change, attribution of the ever-increasing losses from these high-impact events is still contested. Some research finds climate change to drive the rising costs while other attributes this trend to socioeconomic factors such as higher population densities, demographical shift, accumulation of wealth and exposure of assets. As of yet no systematic inquiry into this matter has been carried out in Ireland.

This research compiles a dataset of extreme weather events in Ireland between 2000 and 2017 based on an applied financial threshold of €30m. The overall annual losses are adjusted for inflation and emerging trends are identified and discussed. Population change and per capita GDP are considered as important variables in this research due to their potential to exacerbate losses even without any change in their frequency or climate. Temporal trends in population and per capita GDP are discussed as well as emerging spatial patterns in population distribution. Furthermore, loss values are normalized by adjusting them for inflation, population rise and GDP growth to better understand the relationship between losses from weather extremes and societal and economic factors. The results are contextualized in relevant peer-reviewed literature and compared to similar studies carried out elsewhere in the world.

This study, in agreement with similar research implemented elsewhere, establishes an increasing trend in annual losses from weather extremes in Ireland, while also demonstrating that this trend is nullified by population rise and economic growth. During the study period population of Ireland has increased by 26.4%, resulting in 1 million new residents, meanwhile, the per capita GDP has more than doubled. Larger and wealthier populations hold more assets which can be potentially damaged. Losses from weather extremes in Ireland adjusted for population and wealth increase no longer show a rising trend, highlighting the importance of population densities and wealth accumulation as key factors driving the increase in financial damages stemming from weather and climatic extremes.

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I thank all the amazing staff in the UCC Geography Department who work behind the scenes and my fellow postgraduate students Tara, Olive, Rosie and Diarmuid for creating a supportive and hilarious environment to work in.

I wish to dedicate this achievement to my late mother, Halina, who offered me unconditional love and support in all my endeavours.

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List of acronyms

A&E	Accident and Emergency
AEP	Annual Exceedance Probability
AGW	Anthropogenic Global Warming
AO	Arctic Oscillation
CLU	Current Local Currency Units
CPI	Consumer Price Index
CSO	Central Statistics Office
DART	Dublin Area Rapid Transit
DJF	December, January, February
ED	Electoral Division
EPA	Environmental Protection Agency
ESB	Electricity Supply Board
ESWD	European Severe Weather Database
EU	European Union
GDP	Gross Domestic Product
HSE	Health Service Executive
IFA	Irish Farmers Association
IPCC	Intergovernmental Panel on Climate Change
JJA	June, July, August
LTA	Long-term Average
LAT	Lowest Astronomical Tide
MAO	Multi-decadal Atlantic Oscillation
NAO	North Atlantic Oscillation
NDFEM	National Directorate Fire and Emergency Management
NHC	National Hurricane Center
NWTF	National Windblow Task Force
OECD	Organisation for Economic Co-operation and Development
OPW	Office of Public Works
RNLI	Royal National Lifeboat Institution

RWB	Rossby Wave Breaking
SST	Sea Surface Temperature
UK	United Kingdom
US	United States

1. Introduction

1.1 Extreme weather events

Globally, extreme weather events are responsible for far more financial losses than the rise in mean global temperature. Their impacts are devastating and projections for the future show further exacerbation of their frequency and magnitude (Hallegate *et al.* 2006, Bouwer 2011 and 2013). Worldwide, economic losses from extreme weather events were found to have increased fivefold between 1977 and 2006 (Bouwer *et al.* 2007). Despite the ongoing dispute of whether this increase has been caused by the anthropogenic climate change, the projections for the future are unanimous and show a significant rise in financial losses from extreme weather events (Bouwer 2011 and 2013). Projections also show that even if the climatic conditions were to remain constant, the economic losses will continue to soar due to the societal change and economic development (Changnon *et al.* 2000).

1.2 Weather extremes in Ireland

Given the large degree of regional variability in changing frequencies and magnitudes of weather extremes as well as economic and societal factors, impacts of extreme weather and climatic events need to be studied at an appropriate level (Zhai *et al.* 2018).

The island of Ireland located on the North Atlantic fringe of Europe is particularly vulnerable to Atlantic storms and their associated damaging winds and surges as well as extreme rainfall events and flooding. According to Munich Re reinsurance company (2018), losses from natural disasters between 1980 and 2017 have costed Ireland approximately US$ 4.5 billion. All but four of the events which contributed to this figure were either storms, hurricane tail-ends or floods. According to the study by a team of researchers lead by Hinkel *et al.* (2010), sea level rise and coastal flooding will cause US$ 17 billion in associated damages by 2100 in the European Union (EU). The same study shows that appropriate adaptation measures have the potential to reduce these damages by factors of 7 to 9.

Attribution studies, climate modelling and trend analysis of historical records are all important to inform policy and adequate adaptation strategies as projections indicate exacerbation of economic losses from extreme weather (Bouwer 2011 and 2013). To date, in Ireland, extreme weather events and the economic losses they generate have not been systematically inventoried and therefore, there is no basis on which to perform analysis or identify trends.

1.3 Research aims and objectives

This study aims to put together an inventory of extreme weather events in Ireland, spanning an 18-year period between 2000 and 2017. It also proposes a single methodology which can be applied to extend this dataset in time and to include future as well as past events. Some past attempts to build such a dataset were made, but all proven inconsistent and/or incomplete upon scrutiny; each of them is discussed in more detail in chapter 3. This research attempts to identify and select all weather extremes affecting Ireland during the set study period that meet the clearly drawn criteria and thresholds, as only a systematically compiled dataset has any relevance for further analysis and scrutiny. Meteorological conditions leading up to an event are considered as well as the resulting damages and associated economic losses. Furthermore, this study aims to identify any emerging trends in economic losses from extreme weather events in Ireland and compare those with societal change such as economic development, population rise and demographical shift. The relationship between the rising costs of weather extremes and various socioeconomic factor is discussed in much detail in chapter 2.

1.4 Study overview

Literature review (chapter 2) begins by introducing the issue of anthropogenic climate change and the consequences for weather extremes in the ongoing shift in climate. Next, available peer-reviewed literature on the impacts of extreme weather events is critically considered, including an extensive review of the relationship between increasing losses, climate change, societal factors and economic development. Chapter 2 also identifies ongoing scientific disputes and challenges in disaster loss attribution to which the findings of this study are later related.

Chapter 3 discusses the methods used in each stage of this study. It acknowledges methods adapted from other similar studies, data sources used and identifies challenges and ways in which they were overcome.

The fourth chapter is a chronologically arranged inventory of extreme weather events selected for this study based on methods laid out in the preceding chapter. Each of the included events opens with a summary page briefly contextualizing its occurrence and providing some quantitative data. This is followed by a more in-depth analysis of the meteorological situation leading up to the event as well as an overview of its socioeconomic impacts. Lastly, maps illustrating various aspects of the event are also included.

Chapter 5 attempts to present the findings of this research in the context of other research on the subject. Different component themes are presented in a logical order in which they were investigated. Quantitative data are illustrated in the form of graphs and histograms, emerging trends and patterns are identified and contextualized.

Chapter 6 further discusses the findings of this study, draws conclusions and relates them to the relevant literature reviewed in chapter 2. Opportunities for further research are also identified.

2. Literature review

2.1 Anthropogenic climate change and climate variability

The level of agreement on the human-induced global warming among the scientific community is very high. Polls and analysis of peer-reviewed publications quantify the scientific consensus at 97% (Cook *et al.* 2016). Research also shows that the level of consensus rises with the level of relevant scientific expertise and is the highest among the actively publishing climate scientists (Doran and Zimmerman 2009). The Intergovernmental Panel on Climate Change (IPCC; 2014) claims that the warming of the Earth's climate is *unequivocal* and identifies the human influence as the leading driver of climate change. But the human-induced climate change is not a new notion; the first connection between the burning of fossil fuels and the warming climate was made by a Swedish scientist Svante Arrhenius in 1896. However then, the discovery was thought insignificant in the face of natural forces driving the planet's climate (Arrhenius 1896, Maslin 2004).

Although the Anthropogenic Global Warming (AGW) is now rarely contested and its science is progressively well-understood, the attribution of extreme weather and climatic events is still challenging (Kerr 2011, Bouwer 2019). The first IPCC Assessment Report (1990) concluded that even though the mean average temperatures have experienced small increases, the notion of increased frequency of weather and climatic extremes is not supported by evidence (Hay *et al.* 2016). In its Second Assessment Report, IPCC (1995) concluded that no adequate data exist to establish whether variability of the global climate and its extremes has changed. While the report noted some changes in climatic variability on regional scales, it admitted, that at that point in time, it was impossible to attribute those changes to human impact.

Nonetheless, advancements in climatology and computer modelling in the last two decades proved, that greenhouse gas increases is not only responsible for the rising global mean temperatures, but also entails changes in the weather extremes (Kerr 2011, Fischer and Knutti 2015, Hay *et al.* 2016). The fourth IPCC report already noted that ‘where extreme weather events become more intense and/ or more frequent, the economic and social costs of those events will increase’ (IPCC 2007, pp. 12).

Extreme weather events, although rare, are a natural part of the climate system. The natural variability of climate and the periodically changing large-scale dynamics inevitably result in weather extremes. However, natural climatic phenomena coupled with climate change lead to changes in the frequency, distribution, magnitude, duration, extent and timing of extreme weather. The relationship between the rising global mean average temperature and the climate extremes is complex and non-linear. The shifting patterns of extreme weather may include a decrease in frequency of occurrence of certain types of events and increase the possibility of unprecedented extremes appearing as a result of the altered conditions (Easterling *et al.* 2016, Seneviratne *et al.* 2012). Overall, occurrences of extreme weather are expected to become more frequent under the changing climate (Mahapatra *et al.* 2018).

2.2 Extreme weather and climate events

A special IPCC report (Seneviratne *et al.* 2012) on the changes in climate extremes and their impacts on the natural physical environment, gives the following definition of the weather/ climate extremes:

‘An extreme (weather or climate) event is generally defined as the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends (‘tails’) of the range of observed values of the variable. Some climate extremes (e.g., droughts, floods) may be the result of an accumulation of weather or climate events that are, individually, not extreme themselves (though their accumulation is extreme). As well, weather or climate events, even if not extreme in a statistical sense, can still lead to extreme conditions or impacts, either by crossing a critical threshold in a social, ecological, or physical system, or by occurring simultaneously with other events. A weather system such as a tropical cyclone can have an extreme impact, depending on where and when it approaches landfall, even if the specific cyclone is not extreme relative to other tropical cyclones. Conversely, not all extremes necessarily lead to serious impacts' (Seneviratne et al. 2012, pp. 111).

Given the various thresholds and conditions by which events may be recognized as extreme, their classification appears to be somewhat arbitrary (Meehl *et al.* 2000). This view is also found true for large-scale weather events by Hallegatte *et al.* (2007); according to the authors such events are defined by their societal implications and the amount of publicity they receive, which makes their classification arbitrary and unsystematic.

2.3 Socio-economic implications of weather extremes and their attribution

Weather extremes are an important aspect of the ongoing shift in climate, and a serious challenge to the present-day society with the significant societal and economic impacts they generate (Hay *et al.* 2016, Meehl *et al.* 2000, Huggel *et al.* 2013). Extreme weather and climate events make a strong manifestation in the socioeconomic system, representing the financial impacts of climate change impacts in a more apparent manner than the increases in mean temperature (Hallegatte *et al.* 2006). Globally, extreme weather and climate events produce in excess of US$ 50bn in losses and 250,000 fatalities every year (Mahapatra *et al.* 2018). While the contribution of anthropogenic climate change to the increase in losses from weather and climate extremes in the observed historical records is often contested, virtually all projections agree that future losses resulting from extreme events will increase (Bouwer 2011, 2013 and 2019).

The trends in impacts of extremes are a function of both climatological and societal factors. Current demographic trends such as the ever-increasing population densities, especially in coastal locations, make more people and their accumulated wealth vulnerable to extreme weather. Predictions show that without a shift in societal practices, the socioeconomic losses will keep rising even without any changes in climate (Changon *et al.* 2000, Bouwer 2011). This increasing vulnerability is well illustrated by Bouwer *et al.* (2007), who estimated that if the 2005 Mumbai flooding was to take place in 2015 (under the same climatic conditions), it would cause 80% more financial damage and affect 20% more people. Moreover, continued warming of the climate will further exacerbate losses from extreme events (Changnon *et al.* 2000, Bouwer 2011).

Changnon *et al.* (2000) show that disaster-related losses in the United States have tripled since 1960 while Bouwer *et al.* (2007) found a fivefold increase in global economic losses from extreme events in the last 30 years. Both papers note however, that these dramatic increases can be attributed to growing societal vulnerability rather than climate change. After adjusting the figures for societal factors no upward trends emerge. Changnon and his colleagues (2000) also found that there were no clear long-term trends in weather and climatic extremes to accompany the rising loss figures.

In agreement with Changnon *et al.* (2000), Mechler and Bouwer (2015), Bouwer *et al.* (2007) and Pielke Jr *et al.* (2005), all ascertain that the ever-increasing financial losses resulting from extreme events can be attributed to societal practices and increased vulnerability. The researchers insist that the soaring financial losses are not presently reflected in the trends of weather and climate extremes, while allowing for such discovery to be made in the future. Indeed, climate models accounting for the changing climatic conditions predict that the frequency of weather and climate extremes will increase in the future (Mahapatra *et al.* 2018).

Changnon *et al.* (2000) also investigated the historical record of death tolls associated with extreme events in the United States and found, that apart from deaths resulting from heatwaves and droughts, there was no rise in the number of extreme event victims. In the case of heatwaves, societal factors have once again biased the trends. Changnon *et al.* (2000) explain that the rise in heatwave-related deaths can be attributed to the change in age and poverty demographics. The cause of the increased number of flood-related deaths has not yet been sufficiently investigated.

Bouwer (2011) shows that the number of deaths resulting from particular types of events is relevant to the socioeconomic development of the country. For example, the number of landslide, windstorm and flood victims is higher in the developed world, while the loss of life due to earthquakes and extreme temperature is higher in the developing world. In addition, Bruce (1999) and Bouwer (2013) note that disaster mitigation measures such as improved building design and early warning systems have had an impact on the number of disaster-related deaths.

Mahapatra *et al.* (2018) analysed deaths from weather extremes in India during 2001 – 2014 and discovered that over 1500 events produced at least a single fatality during that period. Overall, weather extremes were responsible for 5 deaths per million of citizens. The number of fatalities associated with extreme precipitation, flooding and cyclones was found to decline over time, which could be at least partially attributed to the adaptive capacity of communities. Meanwhile the number of deaths from lightning and heatwaves has increased. Moreover, death toll of extreme temperature is expected to further increase with progressing urbanization (Mahapatra *et al.* 2018).

As mentioned before, the issue of attribution of rising economic losses to more frequent and increasingly violent weather and climate events is still widely contested. Not all research ascertains that societal practices, rising population and development are the sole causes of mounting costs of natural disasters.

Höppe and Grimm (2009), among others, attribute the upward trends in disaster-related losses to changes in the atmospheric environment induced by the global warming. Based on the analysis of NatCatSERVICE database of natural disasters compiled by the world's leading reinsurance company Munich Re, Höppe and Grimm (2009) conclude that the overall number of natural disasters has increased greatly since 1950. They also find that this increase is mostly due to weather-related events, and that it is not reflected by trends in geophysical events such as earthquakes, tsunami waves or volcanic eruptions. Based on this distinction in the origin of events, a significant role of climate change in the increased number of natural catastrophes and their costs is assumed.

Furthermore, Höppe and Grimm (2009) perform an analysis of the historical records of hurricane activity adjusted for Multidecadal Atlantic Oscillation (MAO), and they conclude a significant increase in the frequency of occurrence of major hurricanes (Saffir–Simpson hurricane wind scale 3 - 5). This upward trend is in turn identified as an impact of global warming, yet societal changes are suggested as the likely main driver of increasing losses.

Höppe and Grimm (2009) reference multiple publications to support the existence of a causal link between extreme events and climate change, not all of which actually affirm that relationship. Of the eight referenced publications, two note about modelled projections for the future rather than present reality, two note rises in sea surface temperatures (SST) without linking it to weather extremes, two report increased tropical cyclone activity without attributing its cause, one links increased risk of severe heatwaves with human activity, while another three establish a link between the rising SST and the increased duration and intensity of tropical cyclones. Effectively, only half of the referenced publications in fact correlate the increased potential for extreme events with climate change, some of which indirectly.

A study by Schmidt *et al.* (2009) also utilized the Munich Re's NatCatSERVICE database for their analysis of tropical cyclone damages in the eastern United States, as no other consistent evaluation of these events was available for the period 1970 - 2005. The adopted methodology was to adjust the upward trend in losses from tropical cyclones for the economic development and societal change and quantify the remaining increase. An annual increase in losses of 4% was found which could likely be attributed to the increase in frequency of tropical cyclones, at the same time human factors are still regarded as a major reason for the increasing losses. These results are heavily dependent on adopted methodology and the spatial and temporal extents of this research are very limited. While a regional trend has been found, the conclusions should by no means be extended over other areas. These are in agreement with the 4th IPCC Assessment Report (2007) which concluded that the anthropogenic contribution to regional increases in the numbers of tropical cyclones is likely (Schmidt *et al.* 2009).

Another body of research utilising data from major reinsurance companies (Munich Re and Swiss Re) is carried out by Bruce (1999). The study focuses solely on major weather and climate extremes, which it defines as those costing more than 1% of the affected country's annual GDP, impacting on more than 1% of its population or causing more than a hundred casualties. An argument is made that the rate of growth in direct economic losses from major disasters is far more rapid than that of population growth or GDP increases (consistent with the previously mentioned findings of Schmidt *et al.* 2009). The inconsistent rates of increases between the losses stemming from weather and climate related events and those resulting from geophysical disasters are noted (Bruce 1999).

Bruce (1999) also argues that modelled projections support insurance companies claims of direct links between the anthropogenic climate change and rising number of extreme events, and while most scientists agree on the projections for the future (Bouwer 2011 and 2013), modelled outcomes of the future are not necessarily reflecting the historical record.

While supporting the notion that climate change has already contributed to extreme events, Bruce (1999) is very careful in drawing conclusions, and evaluates each type of weather extreme separately and admits that societal change is a major contributing factor, and also addresses the effect of land use change on flooding and droughts. Bruce (1999) concludes that some increases in losses can be attributed to climate change impacts, but only regionally and only in the case of heavy precipitation events and extratropical storms.

The direct influence of climate change on the mounting economic losses was also investigated by Mills (2005) who similarly to others (Höppe and Grimm 2009, Bruce 1999, Schmidt *et al.* 2009) admits that societal factors play an important role in the rising costs of extreme events, at the same time presenting evidence attributing upward trends in losses to more frequent weather extremes. Mills (2005) points out that various societal factors obscure the trends and that untangling them is very challenging. He concludes that regardless of the present trends, future impacts of climate change will be magnified by the societal practices and economic development.

As presented above, the issue of identifying the causes of soaring economic losses in the recent decades remains unsettled. The primary causes of increasing losses are the economic development, demographical shift and population rise. Projections for the future show that the variability of the weather system will change and result in more frequent and more violent events (Rosenzweig 2001). The issue of attribution of costs of past extreme events however, is still widely contested. Nevertheless, even the studies attributing part of the increasing losses to extremes driven by climate change, still identify socioeconomic factors as the primary influence on the trends. In their contribution to the Third IPCC Assessment Report, Vellinga *et al.* (2001) attribute the rising costs of weather extremes partially to socioeconomic factors and societal change and partially to changes in the climate system. This attribution is not made without acknowledging large regional variability and differences between changes in particular types of extremes.

An attempt to settle the attribution debate was made by Bouwer (2011), who selected and compared 22 studies on trends in disaster losses. The studies were selected based on their compliance with two main inclusion criteria, namely good systematicity of their approach and the analysed data spanning a minimum period of 30 years. 11 of the studies focused on the United States, 2 on Australia, 3 on Europe, 4 on Asia, 1 on South America and one was global. The general methodology of the selected studies was to normalize the discovered trends of increase in economic losses from weather disasters for societal change and economic development. As established by Bouwer (2011), 14 out of the 22 analysed publications showed no trend in losses after adjustments were made for human factors. The remaining 8 studies all showed upward trends in losses, however upon scrutiny, Bouwer (2011) identified flaws and biases in the methodologies of these publications which strongly undermine their findings. Bouwer (2011) concluded that all 22 investigated studies identify increased exposure and wealth accumulation as the main reasons for the rising costs of natural disasters; while none of the analysed studies pointed to human-induced increase in weather extremes as a major driver of the trends. It is also noted that the influence of climate change on disaster losses is projected be more apparent in the future, than it was found in the observed historical record. In another publication Bouwer (2013) states that up until the year 2040, the contribution of human factors towards increased losses will remain equal or larger than that of human-induced climate change.

2.4 Challenges and uncertainties in disaster loss attribution

The main reasons for the difference of opinions on attribution of rising costs of weather extremes include a lack of centralized gathering of standardized data on losses and systematic approaches in their evaluation (Bruce 1999, Changnon *et al.* 2000, Kunkel *et al.* 1999). Historical sources often do not specify their methodologies, hence it is difficult to know what do the financial estimates encompass and what they leave out, i.e. losses from trade (Bruce 1999, Changnon *et al.* 2000). Changnon *et al.* (2000) also argue the incompleteness of disaster records due to the record-setting extremes being thoroughly scrutinized and the less significant events going on undocumented.

Other challenges include artificial inflation of the loss figures to make them qualify for disaster relief funding (Bruce 1999), a large proportion of data being in possession of insurance companies and not readily available (Bouwer *et al.* 2007) or inherent difficulty in quantifying things like risk or exposure (Bouwer 2011).

Bouwer (2011) also draws attention to the issue of fluctuations in the natural climatic variability, suggesting that large scale atmospheric dynamics may periodically affect the numbers of weather extremes and hence inflate the loss trends despite the adjustments made for socioeconomic factors. A larger number of events can affect short-term trends regardless of their individual severity or extent (Bouwer 2011). Nonetheless, attribution studies show that AGW was a contributing factor in the occurrence of at least some extreme weather events (Huggel *et al.* 2013)

Issues discussed above and the various methods used to adjust the data for socio-economic factors, may obscure the true trends in disaster losses. Bouwer *et al.* (2007) articulates the need for a centralized and peer-reviewed database to advance the research in the loss attribution field.

2.5 Adaptation and risk and exposure reduction

Regardless of their attribution, the global losses from weather and climate extremes have been growing exponentially in the recent decades and according to model projections this trend is likely to continue into the future (Bruce 1999). Moreover, Bouwer *et al.* (2007) suggest that at the current pace the increases in losses from weather extremes will surpass the rates of economic growth. Projections also show that the losses will continue to soar even under constant climatic conditions (Changnon *et al.* 2000, Bouwer 2011), and while mitigation efforts have limited the numbers of casualties (at least in the developed world), they have little influence on the financial losses (Bruce 1999). Nonetheless, Bouwer (2019) remarks that future economic growth and development may lead to increased investments in adaptation and risk reduction which in turn will likely reduce economic losses from extreme weather. Hoeppe (2016) suggests that adaptation and protective infrastructure have the potential to even lower the losses despite increasing risk.

Adaptation is slow. Losses from natural disasters have increased fivefold in last 30 years. There is a strong need for societal change and mitigation measures (Bouwer 2011). Some communities have a larger adaptation capacity than others, but all must enhance their adaptive capacity in order to meet the present and future climatic extremes (Adger *et al.* 2003). Unfortunately some of the poorest and least resilient communities are also among the most vulnerable. Bruce (1999) suggests that while risk assessment protocols should be re-evaluated all around the globe, attention should be drawn especially to some of the poorest communities, often living in very densely populated informal settlements. Recurring major weather extremes can set the economic growth of developing countries even several years back, since they don’t have the financial capacity needed for quick recovery. Developing countries experiencing frequently recurring natural catastrophes also struggle to accumulate financial capital required to advance their economies (Hallegate *et al.* 2007).

Rosenzweig *et al.* (2001) draw attention to the present and future impacts of weather and climate extremes on the global food production and food security. The authors discuss the influence of climatic conditions on crop yields, pest activity and associated use for pesticides and conclude that increased occurrence of extreme events, especially floods and droughts, have an adverse effect on food production. Rosenzweig and her colleagues (2001) find that the changing climate will have its most detrimental effects on food production in the developing world, where the food prices are expected to rise and the risk of malnutrition is expected to be higher.

The themes of risk assessment, mitigation and preparedness recur throughout the relevant literature as the adequate means of building resilience and increasing adaptive capacity (Bruce 1999, Rosenzweig *et al.* 2001). Some studies show that adaptation and risk reduction measures have already contributed to a decrease in losses, at least regionally (Zhou *et al.* 2013), this however has not been sufficiently investigated in the European context.

In Ireland floods are the most common weather extreme and generate a majority of severe weather-related losses. In 2018 a new 10-year flood relief programme worth €1bn was launched by the Irish government, involving 118 flood relief schemes throughout Ireland aiming to protect flood-prone sites (MacConnell 2018).

3. Methodology

3.1 Previous inventories and research

Despite some examples of databases of weather extremes that focus on or include Ireland, this research could not identify a single resource which adopted a systematic approach which would allow for consistent comparison and trend analysis of extreme weather events in Ireland over time. At the same time these incomplete inventories proved a great resource for finding weather extremes and compiling a preliminary list with which to work. Five such datasets and inventories were especially helpful and merit acknowledgement.

1. Met Éireann's Major Weather Events (https://www.met.ie/climate/major-weather-events) is a list of natural disasters which affected Ireland and extends back as far as 1798. Each included extreme is issued with a report that gives an overview of the event and in many cases provides analysis of the causal factors and weather data. These reports however vary from brief notes to comprehensive analysis, have no standardized structure and usually include no information on the socioeconomic impact of the event in question. There is also no information on which events were selected for the inventory and on what basis, and upon scrutiny it quickly becomes apparent that many important and disastrous events are missing.
2. OPW's Flood Hazard Mapping Website (https://maps.opw.ie/) is an extensive database of floods in Ireland, where maps, photographs and official reports can be found for flooding events of all magnitudes. The obvious downside of this resource is its sole focus on one type of weather extreme as well as non-standardized entries.
3. Munich RE's NatCatSERVICE (https://natcatservice.munichre.com/) is a remarkable resource as an archive of natural disasters worldwide and their socioeconomic impacts. It is also the only dataset of weather extremes in Ireland with a defined event inclusion criteria and methodology. Nonetheless, upon closer scrutiny, many discrepancies and inconsistencies in the data for Ireland were found which the company struggled to clarify upon request.

Further inconsistencies were encountered upon comparison with other sources and while overall NatCatSERVICE is perhaps the best inventory of weather extremes in Ireland to date, it is still somewhat miscellaneous, lacks precision and transparency.

4. European Severe Weather Database (ESWD; https://www.eswd.eu/) is a database of weather extremes for all of Europe and its archives can be searched by locality, type of the event, and date of its occurrence. Rather than compiling a single comprehensive report, the database contains many entries for the same event. For example, for Storm Darwin the database returns seven entries, none of which identify it as a major storm wreaking havoc across much of Ireland, but rather as 6 separate instances of locally damaging severe wind and an unconfirmed tornado. In addition, the entries are extremely brief and sometimes concern trivial affairs in the face of the overall scale of an event.
5. Another very valuable resource in this research was data obtained from The Insurance Institute of Ireland (https://www.insuranceireland.eu/) on the cost of extreme weather events in Ireland 2000 - 2018. These data provide consistent and trustworthy estimates of total insurance claims stemming from a particular event. Unfortunately, there is no disclosed methodology and the data are available only on post-2000 events.

3.2 Challenges

There is a large degree of arbitrariness in classifying weather events as extreme, due to the lack of a single definition and a variety of adopted thresholds and conditions or lack thereof (Meehl *et al.* 2000).

In the Irish context, attempts to understand past weather events are difficult due to systematically collected and calibrated weather data records often being inadequately short or simply unavailable. This is the main obstacle in setting out statistical thresholds for recognizing weather events as extreme.

Historical sources such as press articles and government bodies' reports are often the only source of information on the socioeconomic impacts of past weather extremes, unfortunately, data such as estimates of financial losses are rarely accompanied by an explanation of what exactly do they encompass.

In case of both weather statistics and economic losses, data are harder to obtain for less recent events. With older events additional challenges lie in change of recording instruments, weather station relocation and data calibration, as well as simple scarcity of data and comprehensive reports.

Hence while there are challenges to obtaining consistent data on both weather statistics and economic losses, it proved much more viable to focus on the latter and adopt it as the main criteria in this research.

3.3 Adopted weather extreme definition

NatCatSERVICE data was used to perform trend analysis by other researchers (Höppe and Grimm 2009, Schmidt *et al.* 2009), it qualifies events as extreme based on the losses and fatalities caused, and the thresholds vary between countries based on their annual GDP. For Ireland, as a country in the high income group, this threshold is set at minimum of 1 fatality and/or $3m (approx. €2.65m) (Munich RE, personal communication, May 2018). Though as discussed before, this dataset for Ireland proved to be inconsistent and problematic.

Other research cited in Bruce (1999) set the threshold for natural disasters at 1% of country's annual GDP in damages, affecting more than 1% of its population or resulting in 100 or more deaths. These thresholds are set much too high for the scale of extremes affecting Ireland.

This study adopts a financial loss threshold of €30m (January 2018 value) which is equivalent to an annual GDP (2017) of approx. 500 Irish people.

Despite this definitive criterion, inclusion and categorizing of some events comes down to a judgement call, for example, in case of events which were minor in meteorological terms and/or highly localized in their extent, and met the financial threshold only because their impacts were exacerbated by human factors.

Events of the same type occurring in short intervals are considered as one cumulative event (i.e. cyclone clustering or recurring floods) if they share a common cause and where each component-event doesn't meet the threshold. However, where one of the events in the series is of an extraordinary magnitude and meets the damage threshold independently it is treated as a separate event.

The main source of information on past weather extremes to consider in this research were the five directories discussed in section 3.1. Sometimes, while scrutinizing a particular event, its comparisons to other historical events of the same type were encountered and allowed a discovery of previously unknown events, which would then be separately investigated and considered.

3.4 Weather data

Weather data was instrumental in conducting this research. It informed the writing of event profiles, allowed for statistical comparisons between events and provided the basis for the maps.

Virtually all weather data (unless stated otherwise) utilised in this research were sourced from Met Éireann's website or publications. Due to the majority of weather extremes in Ireland being hydrological in nature (floods and storms), the daily and monthly "Redistribution of cumulative rainfall values" dataset spanning periods 1960-2016 and 1960-2017 respectively, was an invaluable resource in this research. Unfortunately in case of many other analysed events, the available records included too few stations or spanned too short time periods to perform any significant analysis such as return period estimation or 99th percentile exceedance. In Ireland, variables such as wind speed and direction, temperature or snow depths are recorded at far fewer stations than precipitation is. Moreover, data records available via Met Éireann's website are of short duration- often limited to less than 20 years.

As of May 2019 collaborative efforts are being made by Met Éireann, Central Statistics Office (CSO) and Maynooth University to rescue and digitize weather data records previously only archived in paper form, many of which stretch back into the mid-1800s (Met Éireann 2019).

3.5 Data on financial losses

As acknowledged by others, data on losses from extreme weather events are generally not easily found (Chagnon *et al.* 2000, Bruce 1999). In this study an attempt is made to provide financial estimates for damages caused by each included event, including the overall loss amount as well as its insured component. In most cases these data were provided either by the Insurance Institute of Ireland (pers. comm. June 2018) or Munich Re (pers. comm. May 2018), but also sourced from press articles and various reports.

As informative and helpful as Munich Re's staff were in providing assistance to better understand the methodology of their online natural disaster database NatCatSERVICE (https://natcatservice.munichre.com/), the company's policy allowed them to share only annual aggregate losses for Ireland while loss values for individual events were only shared if they came from a third party and were not Munich Re's own estimates. It was possible to extract loss values for individual events directly from NatCatSERVICE, only if the event in question was the only one of its type (geophysical, meteorological, hydrological or climatological) in a particular year. Values obtained in this way, however, were in 2017 US$ and the company failed to provide the exact conversion algorithm. A method of converting these values back to their original EUR values was established and validated with 23 events for which both original EUR values and 2017 US$ values were available. The identified margin of error was 3.7% and it can be attributed to rounding up of the 2017 US$ values.

For some events loss values were only available for either the overall losses or their insured component. In such cases the insured component of all other events with complete loss data was calculated as a percentage of their respective overall losses, and the average served as means to extrapolate the missing values.

3.6 Adjustment for inflation and socioeconomic factors

For the ease of comparison loss figures are also adjusted for inflation. This is done using the Irish Central Statistics Office's Consumer Price Index Calculator (https://www.cso.ie/en/interactivezone/visualisationtools/cpiinflationcalculator/) and represented in their respective January 2018 values. Where an event spans more than a month, mean value for all relevant months is converted to January 2018 worth.

To quantify the relationship between rising loss values and socioeconomic factors, a normalization algorithm (Eqn 1.) similar to that utilized by Pielke Jr and Landsea (1998) is applied as follows:

$$NL_{2018} = L_{2018} * GDP_y * P_y$$

Eqn 1. Loss normalization algorithm.

Where NL_{2018} = the loss normalized to its 2018 value, L_{2018} = the loss already adjusted for inflation to its January 2018 value, GDP_y = wealth factor determined by the per capita GDP ratio between the year of event and 2017, P_y = population factor determined by the population change ratio between year of the event and 2017.

The applied algorithm (Eqn. 1) differs slightly from that deployed by Pielke Jr and Landsea (1998) as the loss values were already previously adjusted for inflation. The wealth factor represented by Pielke Jr and Landsea (1998) in fixed reproducible tangible wealth per capita is substituted by the per capita GDP due to availability of data. As observed by Schmidt *et al*. (2009) data on accumulated wealth is more appropriate as the wealth factor than GDP, unfortunately it is unavailable in many parts of the world.

3.7 Return periods

Return periods are given for events when they are available from secondary sources, most times the estimation method and the dataset used are not provided and hence these values should be treated as indicatory rather than definite.

3.8 Fatalities

Historically, with some exceptions, weather extremes in Ireland produce few fatalities, especially in modern history. While loss of human life is acknowledged in summarizing of the events, it is not applied as an inclusion criterion.

3.9 Weather maps

The maps included in this inventory are intended to give a visual representation of the meteorological conditions leading up to or during a particular event or its impacts. In many cases the kind of produced map was dictated by the availability of data. Maps utilize Met Éireann data unless stated otherwise.

3.10 Population change data and maps

As discussed in chapter 2, some studies (i.e. Bouwer 2011, Huggel *et al.* 2013) have exposed a direct correlation between upward trends in losses from weather extremes, societal change and economic development, i.e. through rising population densities within cities or coasts and higher value of exposed assets. To analyse whether similar relationships can be established in Ireland, population change maps are made based on census data. Produced maps show a percentage of population change within each Electoral Division (ED) between 2002 and 2016 (two censuses most relevant to the chosen 2000 - 2017 study period). A map of total population change in Ireland as well as three high-resolution maps of Co. Dublin, Cork and Galway cities are produced to illustrate where the largest population gains and decreases occurred. All four maps utilize Central Statistics Office (CSO) census data. The World Bank (2019a) data on population are used in trend analysis, as these are released annually and are available for the whole study period.

3.11 GDP

Wealth accumulation and concentration is another important factor in extreme weather event loss normalization. Higher per capita Gross Domestic Product (GDP) means more assets at risk, especially in densely populated areas (Bouwer 2011, Changnon *et al.* 2000).

In Ireland, per capita GDP has more than doubled between 2000 and 2017, possibly contributing to the higher concentration of wealth vulnerable to weather extremes. Data on GDP utilized in the analysis chapter come from the World Bank (2019b) and are expressed in per capita, current local currency units (CLU).

4. Inventory of extreme weather events

This chapter is a chronologically arranged inventory of extreme weather events in Ireland which happened between 2000 and 2017. Each of the included events is first summarized in a single-page database-like entry stating its name and type, return period, spatial extent, short summary of impacts, financial loss figures, number of fatalities, narrative of the event and relevant keywords. This is followed by an analysis of weather conditions leading up and during the event and a detailed account of its associated impacts and damages. Finally, there is a map for each entry illustrating a relevant aspect of the event, the choice of maps is dictated by the availability of data.

4.1 2000 November 5 – 7th flooding in the south and east

TYPE OF EVENT: Rainfall/ flood

RETURN PERIOD: up to 100 years in places

EXTENT: South and East of Ireland

IMPACTS: Torrential rain of the 5th led to flooding in most of the south and east of Ireland, with parts of Southern Tipperary, Waterford, Wexford, Kilkenny and Dublin worst affected. Hundreds of properties flooded and evacuated. Cancellations and extensive disruptions to all forms of transportation. Many major and hundreds of regional roads impassable. Some schools closed. Approx. 12,000 properties with disrupted electricity supply.

DAMAGES: €114.9m unadjusted (€152.7m CPI adjusted January 2018), including €51m insured unadjusted (€67.8m CPI adjusted January 2018).

FATALITIES: 1

EVENT NARRATIVE: On November 5th 2000 a frontal depression tracked just south of Ireland bringing heavy rain especially in the east and the southeast of the country. The eastern counties have borne the brunt of the rainfall where it continued throughout November 6th, although by then the centre of the low was approaching Cornwall and began filling. Estimated return periods for the resulting flooding varied from catchment to catchment and while many gauging stations reported return periods of 2 - 10 years, some reported values in excess of 50 years.

KEYWORDS: Frontal depression, low, rainfall, flood, flooding.

Meteorological profile

On November 5th a frontal depression tracked along the south coast of Ireland bringing heavy rain. The depression produced little rain in the west of Ireland as it approached, although the pressure dipped to 971hPa Valentia Observatory, Co. Kerry at 4pm November 5th. Later that day similar lowest sea level pressure values were recorded at Cork Airport and Roches Point, Co. Cork, while the rainfall amounts were higher, with daily totals of 11.3mm and 34.8mm (12am to 12am) respectively. By midnight November 5th the depression reached its minimum central pressure of 968hPa while approaching Cornwall and then began filling as it tracked across southern England. In the east of Ireland where the rain was the heaviest, it continued throughout November 6th further exacerbating the flooding which began on the 5th. Highest 48-hour rainfall was recorded in the Wicklow mountains (with totals in excess of 200mm in places) and adjacent counties. Both September and October 2000 were wetter than usual throughout the country (see table 1), hence the capacity of the soil to receive and hold moisture during this event was largely reduced.

Return periods calculated for the resulting flooding varied in different catchments. Several gauging stations recorded flows and peak levels with return period of less than 5 years. Stations on the Nore and the Barrow Rivers had calculated return periods of 5 - 10 years. Highest return periods were calculated for Boyne (30 years), Suir (25 - 50 years), Ryewater (>50 years) and 25 - 100 years for Slaney (OPW 2000b). The spatial distribution of the rainfall on November 5th 2000 resembled that of Hurricane Charlie of 1986 and was also comparable in severity (Met Éireann 2000, McNally 2000a).

Station	September 2000 [mm]	Percent of LTA	October 2000 [mm]	Percent of LTA
Belmullet	139.4	138	259	186
Casement Aerodrome	74.7	118	80.2	116
Claremorris	103.4	110	211.6	165
Clones	101.1	129	115.7	121
Cork Airport	109.5	111	183.9	136
Dublin Airport	99.9	157	87.3	122
Malin Head	176	176	170.7	147
Mullingar	112	141	152.9	163
Shannon Airport	106.7	133	176.3	178
Valentia Observatory	152.2	120	308.9	182

Table 1. September and October rainfall was significantly above the 1971 - 2000 LTA at all ten queried synoptic stations. Monthly totals ranged from 110 to 176% of the LTA for September and 116 to 186% for October.

Impacts

Torrential rain of the 5th led to flooding in most of the south and east of Ireland, with parts of Southern Tipperary, Waterford, Wexford, Kilkenny and Dublin worst affected (figure 1). This event was described by some as the worst since Hurricane Charlie (McSweeney 2000, McNally 2000a). Instances of school closures as well as court proceedings and sport fixtures cancellations occurred in various counties (Murphy 2000, Hogan 2000). As many as 12,000 homes and businesses had their electricity supply temporarily cut (Humphreys and Donnellan 2000). The ESB dam at Poulaphouca reservoir, Co. Wicklow was forced to stop power generation and release water into the Liffey for safety reasons. While the power station ceased to operate for 24 hours the dam still acted as a flood defence (McNally 2000b). Hundreds of residential and commercial properties were flooded throughout the country, with some properties in Enniscorthy, Co. Wexford inundated to a depth of up to 1.8m; and several hundred people had to be evacuated from their homes (OPW 2000a and 2003, Tipperary S.R. County Council 2000, Dublin City Council 2000, Kildare County Council 2000, McDonagh, Cunningham and Murphy 2000). Many lucky escapes were made; in Mallow, Co. Cork a capsized lorry driver was saved from drowning by a young soldier. In Co. Donegal coast guard rescued 2 canoeists and 4 anglers whose vessel broke down (Humphreys and Donnellan 2000, Riegel 2000). A single fatality resulted from this event, a 68-year-old woman was hit by a farm gate slammed by the raging wind and later died in the hospital from sustained injuries (McDonagh *et al.* 2000).

The severity of this event was perhaps most apparent in disruptions to all forms of transportation. Many primary national roads and hundreds of regional roads were impassable or closed to traffic.

The Automobile Association urged all motorists to refrain from travelling unless absolutely necessary and the spokesman for Bus Éireann offered similar advice to its passengers, calling this event the worst disruption in their services in memory (Cunningham 2000a and 2000b). Many railway services were cancelled countrywide with few exceptions, in Dublin all but one lines were cancelled including the DART. Apart from flooding, two instances of landslides contributed to the cancellations and delays (Cunningham 2000a). At least two transatlantic flights bound for Dublin were redirected to land at other airports and the whole airport’s schedule had an average delay of 2 hours (Cunningham 2000a, O’Keeffe 2000). Most ferry services also cancelled, two ferries bound for Rosslare were unable to dock and so had to turn back (Cunningham 2000a). The road connecting Rosslare harbour with Dublin was impassable due to flooding at Enniscorthy and the Dublin-Rosslare train was cancelled due to a landslide also around Enniscorthy (McSweeney 2000, Humphreys and Donnellan 2000).

Munich Re (pers. comm. May 2018) has estimated the overall losses from this event to be approximately €114.9m, of which €51m were insured.

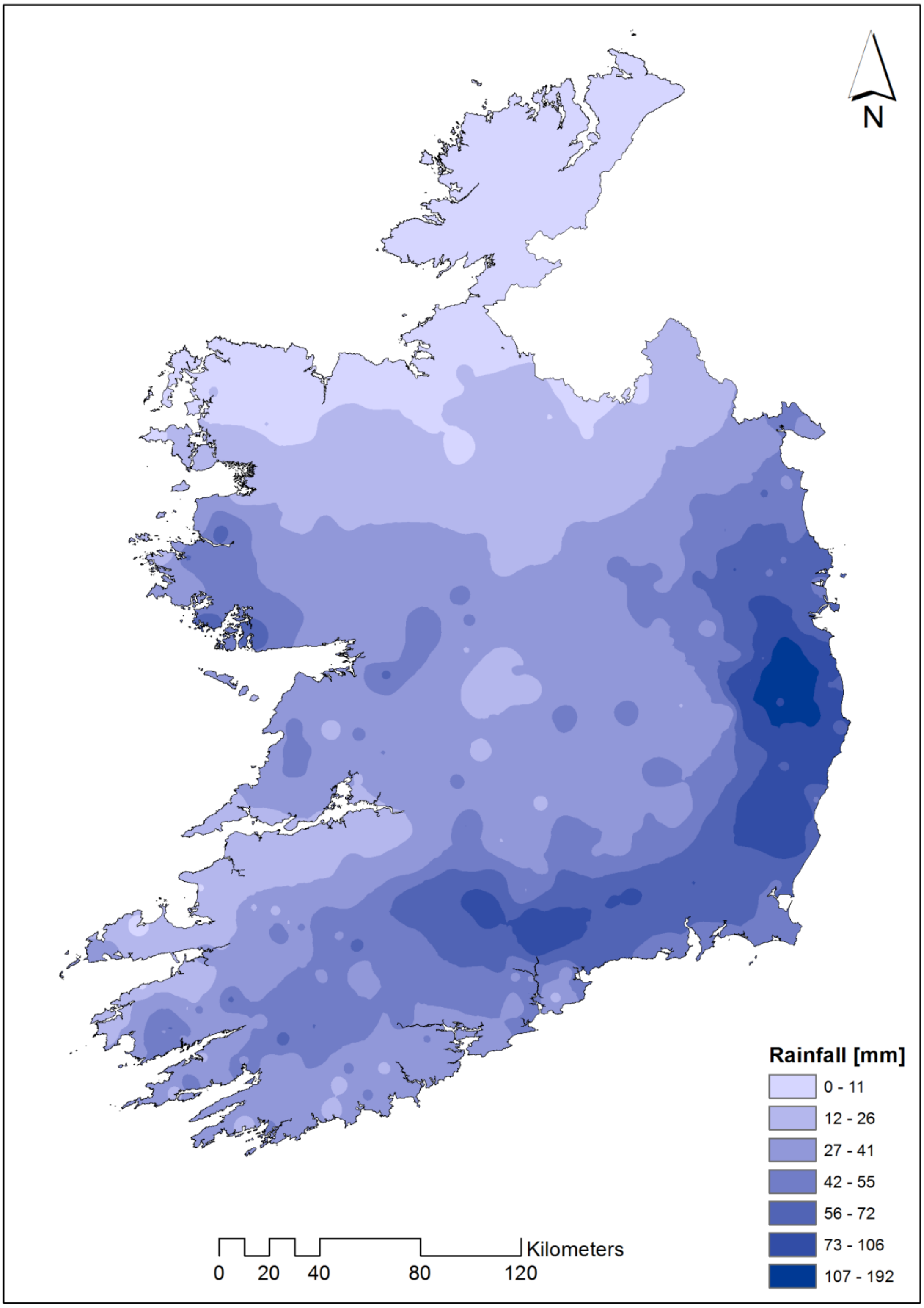

Fig 1. Spatial distribution of the rainfall of November 5th 2000. The east and southeast of the country received most of the rain, Co. Wicklow and parts of counties Dublin and Wexford received in excess of 70mm over 24 hours ending 9am November 6th. Many stations situated in the Wicklow mountains recorded daily totals in excess of 130mm.

4.2 2001, December freeze

TYPE OF EVENT: Cold Spell/ Winter Damage

RETURN PERIOD: N/A

EXTENT: Countrywide

IMPACTS: Overall damages stemming from the cold weather were estimated to be €45m (Munich RE, pers. comm. May 2018), including €30m of insured losses (Insurance Institute of Ireland, pers. comm. June 2018).

DAMAGES: €45m unadjusted (€56m CPI adjusted January 2018), including €30m insured unadjusted (€37.3m CPI adjusted January 2018)

FATALITIES: 0

EVENT NARRATIVE: Persistent anticyclones towards the end of the month brought north-easterly airflow and dry, sunny conditions but also cold temperatures and frequent frosts. Monthly mean temperatures up to and sometimes over 1°C below LTA, number of days with ground frosts over 20 at many stations. Lowest air temperature of -9°C recorded at Fethard, Co. Tipperary.

KEYWORDS: Cold spell, freeze, winter damage.

Meteorological situation

After an unsettled and rainy first week of December, an anticyclone (1044hPa) situated over northern Europe and extending over eastern Ireland began to drift westwards, bringing south-easterly airflow and dry, sunny conditions. By mid-month the same anticyclone centred itself over Scotland and continued to provide Ireland with dry and sunny weather. In the last week of December the persistent airflow changed to north-westerly and brought frequent wintry showers and severe frosts, especially after dark. Northern half of the country experienced the coldest temperatures and local accumulations of snow. Overall it was a very dry and exceptionally sunny December. Despite mild conditions in the first half of the month, mean monthly temperatures (figure 2) were significantly below their long term averages while the number of recorded days with ground frost was above normal. The lowest air temperature was -9^{o}C recorded at Fethard, Co. Tipperary (Met Éireann 2001).

Impacts

Thousands of pipes burst due to freezing temperatures. Overall damages stemming from the cold weather were estimated to be €45m (Munich RE, pers. comm. May 2018), including €30m of insured losses (Insurance Institute of Ireland, pers. comm. June 2018).

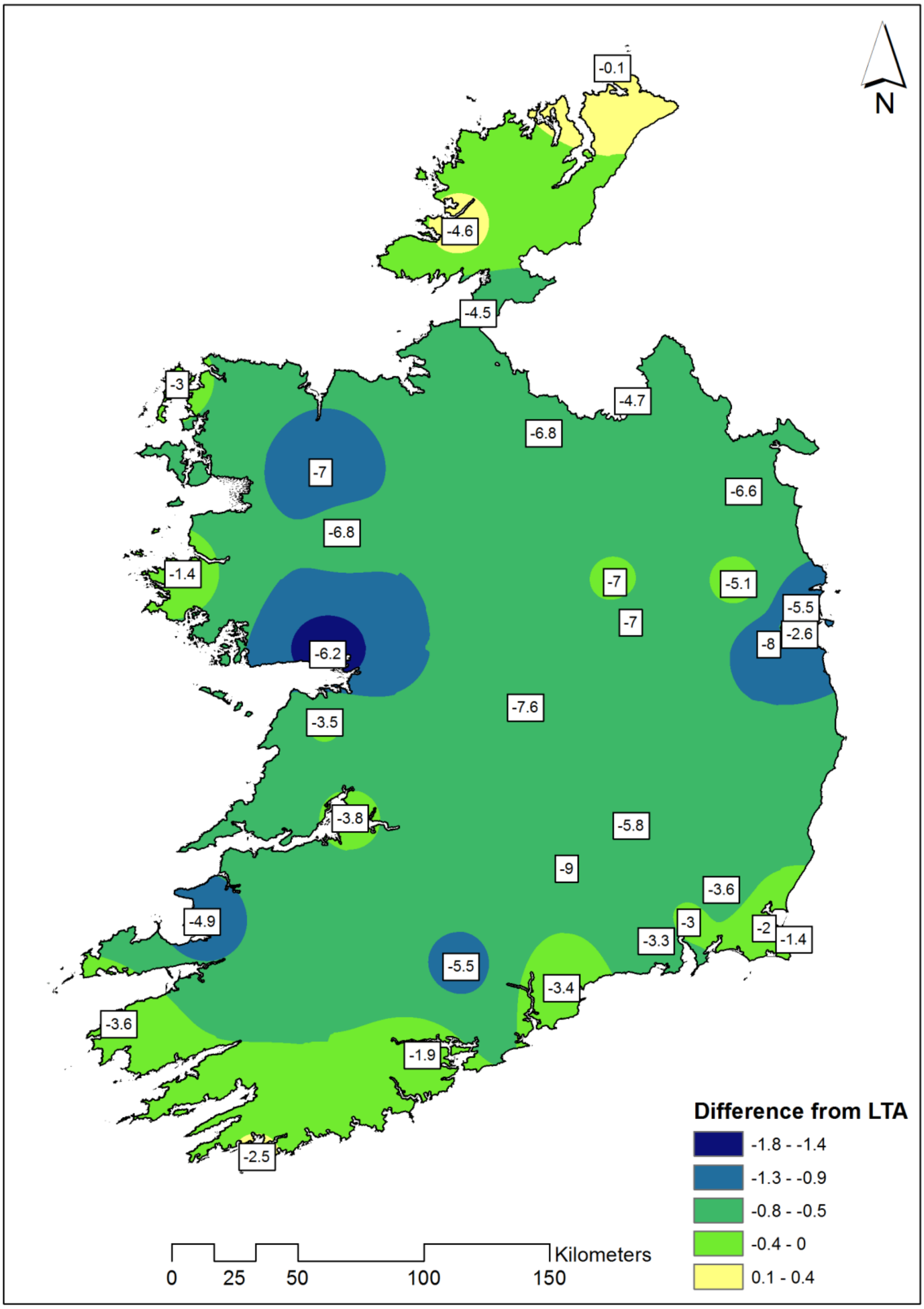

Fig 2. Mean monthly temperature map for December 2001, showing difference from 1961 - 1990 LTA. Values on the map are the lowest recorded air temperatures (°C) that month at a given location.

4.3 2002, February 1st coastal flooding

TYPE OF EVENT:	Coastal flooding/ storm surge
RETURN PERIOD:	>100 years
EXTENT:	Dublin worst affected, with some flooding and damages along east and southeast coasts.
IMPACTS:	Coastal defences were breached by the waves causing flooding and damages in the coastal areas of Dublin. Main rivers in the city affected by the exceptionally high tide and burst their banks. Traffic, bus and rail services badly disrupted, flights at Dublin Airport delayed. Hundreds of houses badly flooded and without electricity. Coast guard and RNLI rescued some 100 stranded people. Major damage to infrastructure with hundreds of meters of collapsed quays.
DAMAGES:	€115.6m unadjusted (€143.1m CPI adjusted January 2018), including €37m insured unadjusted (€45.8m CPI adjusted January 2018).
FATALITIES:	0
EVENT NARRATIVE:	Unusually high tide further exacerbated by a very deep Atlantic depression passing to the northwest of Ireland resulted in the highest tide ever recorded at Dublin Port. The tide peaked at 5.46m LAT (lowest astronomical tide) which was 36cm higher than the previous record set in 1924 and more than a meter over the forecasted tide height. Devastating surge and flooding. Liffey, Tolka, Dodder and the Royal Canal overflowed.
KEYWORDS:	Storm surge, coastal flooding, rainfall, flooding, flood, high tide, storm.

Meteorological situation

On February 1st 2002 Dublin experienced its highest tide on record, causing the worst flooding event in at least 75 years. The predicted tide for Dublin Port for February 1st at 2pm was 4.44m LAT, and was underestimated by just over a meter as the actual tide peaked at 5.46m LAT (2.95m Malin Head Datum), which was 36cm higher than the previous record set during the 1924 flood. A very deep depression (in the order of 930hPa) passing to the northwest of Ireland and the associated gale-force winds were contributing factors in this event, while rainfall was insignificant and of little importance (Dublin City Council 2002a). During the storm, a weather station in Dun Laoghaire, Co. Dublin recorded atmospheric pressure of 980hPa and wind speeds of up to Beaufort force 10 (>24m/s; Dublin City Council 2002c). Apart from affecting the coastal areas, high tide raised water level in rivers Liffey and Dodder and in the Royal Canal (Dublin City Council 2002a).

Barry and Partners Consulting Engineers employed by the Dublin County Council (2002c) calculated the return period for the tide to be 750 years, while suggesting that the return period of the surge was likely in excess of 100 years.

Met Éireann issued a weather warning for Dublin on January 31st, forecasting gale-force winds, up to 30mm of rain and localised flooding (Dublin City Council 2002a).

Impacts

Dublin City was by far the worst affected but some flooding occurred also in counties Limerick, Louth, Kerry, Meath and Wicklow (Irish Red Cross 2002, Black and Cox 2002). In Dublin flooding began just after 1pm when the Fire Brigade received its first calls from the Ringsend area; the flooding was sudden with no time for people to prepare or evacuate (Dublin City Council 2002a, Irish Red Cross, 2002). Wave action breached coastal defences in many areas and caused flooding, rivers Dodder, Tolka, Liffey and the Royal Canal overtopped their banks in their tidal parts and flooded the surrounding areas. Several hundred meters of quays collapsed in this event (Dublin City Council 2002b, Murphy 2002). The worst affected areas in Dublin were Sutton, Clontarf, East Wall/ North Strand, Ringsend and Sandymount (see location map in figure 3; Dublin City Council 2002a). Dublin City Council activated the Major Emergency Plan at 2.45pm which remained active until 4pm on Sunday, February 3rd (Dublin City Council 2002a). Council staff, the gardaí, civil defence, fire brigade, army and health board personnel were mobilised and some 20,000 sandbags were used in the efforts to fight the flooding. RNLI and coast guard were also mobilised and rescued more than 100 people stranded in their homes and workplaces (Dublin City Council 2002a, Black and Cox 2002, RTÉ News 2002). There were major disruptions to traffic as well as bus and rail services and the flights in and out of Dublin Airport were up to two hours delayed. Hundreds of homes had their electricity supply cut off (RTÉ News 2002, Black and Cox 2002). Hundreds of private residential properties were severely flooded as were many council houses; relief centres were set up throughout the affected areas, army and civil defence operated a field kitchen and alternative accommodation was provided to those in need (Dublin City Council 2002b).

Munich RE reinsurance company estimated the overall damages sustained in this event to exceed €115m (pers. comm. May 2018), while the insured portion of these losses amounted to approximately €37m (Insurance Institute of Ireland, pers. comm. June 2018).

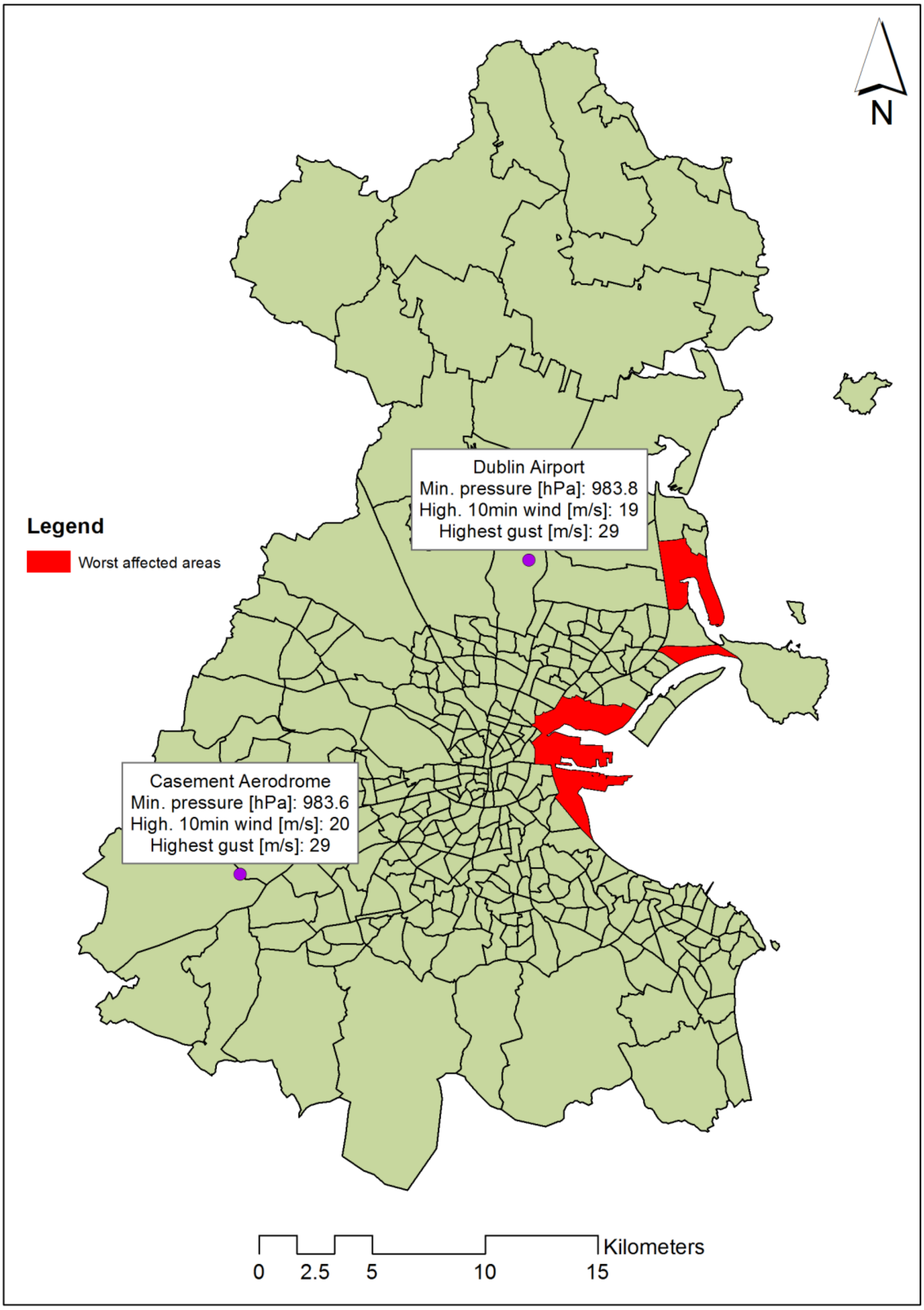

Fig 3. Map of Dublin indicating the areas most affected by the flooding, also showing meteorological conditions during the event at two local synoptic stations operated by Met Éireann.

4.4 2002, November 14/15th flooding

TYPE OF EVENT:	Flood
RETURN PERIOD:	<20 years for 12-hour rainfall 15 – 45 years for 24-hour rainfall. >100 years for the flood.
EXTENT:	County Dublin worst affected with less significant flooding in Cos. Meath, Kildare and Wicklow.
IMPACTS:	Widespread flooding especially severe along Tolka river and North Dublin. Many roads impassable and bus and DART services delayed or suspended. Some 200 people evacuated and evacuation centres set up. Many residential and commercial properties inundated. Army mobilised to assist distressed civilians and fight floodwaters.
DAMAGES:	€68.4m unadjusted (€81.5m CPI adjusted January 2018), including €50m insured unadjusted (€59.6m CPI adjusted January 2018)
FATALITIES:	0
EVENT NARRATIVE:	Following an exceptionally wet October and a very wet first half of November, the fields were approaching complete saturation when a prolonged and very intense rainfall event took place between November 13th and 15th. Some 80mm of rain fell in Co. Dublin over a 38-hour period, producing widespread flooding. Record setting flow rates were recorded in the Tolka river.
KEYWORDS:	Rainfall, flood, flooding, flash flood.

Meteorological situation

On November 13th, a slow moving low pressure system (minimum central pressure of 966hPa) was slowly moving across the Irish Sea and produced an intense rainfall event in the greater Dublin area which lasted 38 hours. The rain began in the evening of the 13th and continued until the morning of the 15th. The peak hourly rates were in order of 15mm and occurred in the afternoon of the 14th. The average accumulation of rainfall in Dublin area over the 38-hour period ending 10am on November 15th was about 80mm. The 24-hour rainfall (ending November 15th at 9am) totals for all three abovementioned stations were among the ten highest since their respective records began (Met Éireann 2002).

The preceding October was the wettest ever at Dublin Airport with 181mm (and second wettest month overall). It was also the wettest month ever recorded at Casement Aerodrome with 178.9mm, and second wettest October at Glasnevin with 161.1mm (6th wettest month). In the first 13 days of November leading up to this event, Dublin has already received some 75% of its average monthly rainfall. Very wet conditions throughout at least 6 weeks resulted in soils at or beyond field capacity already from late October onwards. Soil moisture deficit measured at Dublin Airport and Casement Aerodrome on November 11th was -11mm at both stations, indicating near complete saturation of the ground (Met Éireann 2002).

The Tolka catchment (see location map in figure 4) is rather flat, not very developed and is known to deal well with short-lived intense rainfall events like summer storms. Most of the biggest floods on its record happened during a wet winter and after successive heavy rainfall events, when the soils are saturated and the runoff is high. It were precisely such conditions which led to the November 14/15th flooding which happened to be the worst flood on Tolka's record. A peak flow of 97m^3/s was estimated for the Glasnevin Botanic Gardens, while further downstream at the Drumcondra station, an event of 90m^3/s would have a return period of 100 years. In addition, the second worst Tolka flooding on record- that of December 1954 (85m^3/s), was at the time assigned a return period of over 100 years (Dublin City

Council 2003). It may be so deducted that this event had a return period of in excess of 100 years.

Impacts

Torrential and prolonged rain which fell on a largely saturated catchment led to Tolka and a selection of other rivers to overflow their banks and flood many areas in North Dublin as well as parts of Cos. Meath and Kildare (Dublin City Council 2002, Kildare County Council 2002). Flooding was also reported in Arklow, Co. Wicklow and in counties Clare, Galway, Mayo and Wexford (Cox *et al.* 2002). The flooding on Tolka, which was by far the most significant in this event, began in the early morning hours of November 15th. The rainfall peaked on the afternoon of the previous day, but the flow rates kept rising and peaked with many hours' delay just before 2am on the 15th. The record breaking flow resulted in the river overflowing its banks and serious flooding (Met Éireann 2002).

There were over 200 people evacuated in the North Dublin area and many availed of accommodation in the evacuation centres. A wedding party of more than 100 people required rescue from a hotel in Clonee, Co. Meath and a group of 26 pupils and their teachers from a school in Swords (Dublin) were ferried to safety by firemen after becoming trapped in the building surrounded by floodwaters (Newman 2002, Quinn 2002).

The flooding in Dublin was widespread affecting areas along the river Tolka from Drumcondra to Blanchardstown as well as many areas further north, including Swords, Portmarnock, Rush and Malahide. Many houses and residential properties and roads were flooded (Newman 2002, Fingal County Council 2002). Dublin Bus, Bus Éireann and DART services were disrupted and some cancelled (Newman 2002). Civil defence, Council Staff, Gardaí, Fire Brigade as well as the Military were all mobilised to fight the flooding and assist distressed civilians (Newman 2002).

Insurance claims submitted in the aftermath of the flood amounted to €50m (Insurance Institute of Ireland, pers. comm. June 2018), while the overall losses from this event were estimated by Munich Re to be €68.4m (pers. comm. May 2018).

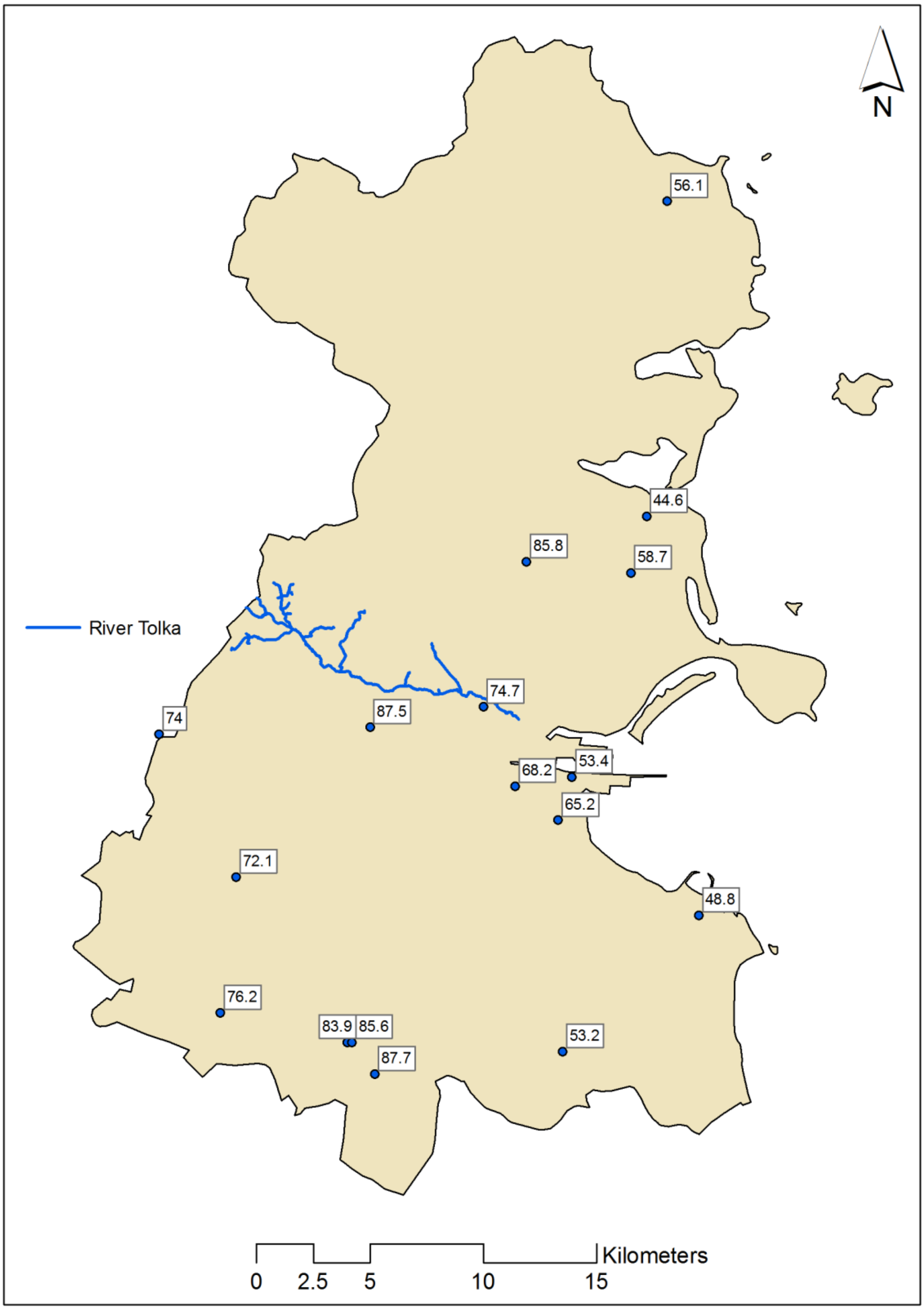

Fig 4. Map of Dublin showing the location of river Tolka and cumulative rain values for the 48-hour period preceding the flooding.

4.5 2004, October 17 – 28th storm and flooding

TYPE OF EVENT: Storm/ flood

RETURN PERIOD: N/A

EXTENT: South and southeast.

IMPACTS: €51.1m unadjusted (€58.1m CPI adjusted January 2018), including €38m insured unadjusted (€43.2m CPI adjusted January 2018).

DAMAGES: Counties Cork, Waterford and Wexford worst affected with cities as well as rural areas inundated. Record setting water levels at several locations including River Lee in Cork City. Traffic, railway, ferry services and flights disrupted. Residential as well as commercial properties flooded resulting in millions of euros worth of losses. Some evacuations reported.

FATALITIES: 0

EVENT NARRATIVE: A very deep Atlantic depression approached Ireland from the southwest on October 27th and hovered around the south coast for some 48 hours bringing heavy rainfall and storm-force south-easterly winds. The coincidence of heavy precipitation, storm surge created by the gales and very high tides resulted in widespread tidal flooding around the south and southeast coasts of Ireland.

KEYWORDS: Rainfall, flood, tidal flood, flooding, storm surge, storm.

Meteorological situation

On October 27th 2004 a rapidly deepening depression approached Ireland from the southwest bringing heavy rainfall and high seas. The low has centred itself over the southwestern tip of Ireland by 12am on the 28th and has remained stationary for the

next 24 hours, before beginning to fill and very slowly move away from Ireland and towards Brittany throughout the 29th (KNMI 2017). Figure 5 illustrates the spatial distribution and intensity of rainfall on October 27/28th. The minimum central pressure of this system was in the 950hPa region (Harwood 2012a, McWilliams 2004), and the winds gusts recorded during the storm were in excess of 110km/h and equal to Beaufort scale 11 described as violent storm (NOAA 2004).
On October 25th and 26th, Met Éireann accurately forecasted heavy rain, stormy conditions and flooding for the south of Ireland. High tide on the 27th occurred at 6:04pm, on the morning of the 28th at 6:22am and again in the evening at 6:40pm (Cork County Council 2004b).

Some 50mm of rain associated with this depression fell in the south and southeast over 27/28th of October. Heavy precipitation, storm surge and south-easterly gale force winds unfortunately coincided with the full-moon and high spring tides. Such set of circumstances, together with a particular longevity of the storm, resulted in widespread and significant flooding especially in the south and the southeast (Harwood 2012a, McWilliams 2004).

In Cork City, the water level in the River Lee was reportedly the highest since 1962 (Harwood 2012a), Wexford harbour experienced record breaking water levels (Wexford County Council 2005) and Dublin Port Station recorded its third highest tide in history (Dublin City Council 2005).

Impacts

A coincidence of several meteorological factors described above led to the significant tidal flooding along the south and south-eastern coast of Ireland, with counties Cork, Waterford and Wexford worst affected (Irish Examiner 2004, Harwood 2012a). There was also flooding further inland, especially along rivers Suir (Waterford), Blackwater (Mallow and Fermoy) and Lee (Cork City; Harwood 2012a, Irish Examiner 2004).

Thousands of homes countrywide had their electricity supply cut off (Irish Examiner 2004). Due to the storm several flights to Cork were redirected to land at other

Airports. Some ferry connections servicing Dublin, Cork and Rosslare had to be cancelled and several railway lines were also closed (RTÉ News 2004, Irish Examiner 2004).

In Cork City alone, millions of euros worth of damages were caused by the River Lee bursting its banks. Streets alongside both channels of the river were inundated, some up to 0.9m in depth (Roche 2004). St. Patrick's and Oliver Plunkett streets, where a lot of Cork's business and retail shopping concentrates, were both badly inundated and hundreds of traders sustained devastating damages (Cork City Council 2019, Hayden 2004). Some motorists were trapped in their vehicles and required assistance from the Fire Brigade (RTÉ News 2004, Roche 2004).

Outside the city, worst affected in County Cork were Passage West, Carrigaline and Youghal- where the storm surge increased the water level 1.5m over the predicted tide height (Irish Examiner 2004, RTÉ News 2004, Cork County Council 2004a and 2005). Crosshaven lifeboat rescued residents of two houses along Crosshaven road and a further six people from a bungalow submerged under 2.4m of water, of whom one was a 77-year-old woman (Cork County Council 2004b, Irish Examiner 2004). Also in Cork County, amidst heavy seas a cargo ship ran aground near Kinsale and began leaking diesel from its 1300 tons tank (Irish Examiner 2004).

In Waterford City, the N25 was flooded together with a number of businesses situated alongside the road, this was exacerbated by vehicles driving through the floodwaters at undue speed. There were also reports of light flooding to some residential properties (Waterford City Council 2004). In Waterford County flooding occurred in many low-lying and coastal locations, most notably in Dungarvan and Passage East. Some localities experienced inundation of up to 1.5m in depth (RTÉ News 2004, Waterford County Council 2004).

Flooding occurred also in many areas of County Wexford, with Wexford town most badly affected. Record breaking water levels in Wexford Harbour inundated the Quays, the Main Street and Redmond Road and Square, many properties in these areas were badly damaged. Lesser, though significant flooding occurred in Enniscorthy where River Slaney burst its banks due to severe rainfall. New Ross town as well as many coastal villages throughout the county were hit by tidal flooding due to a combination of high tide and south-easterly gales (Wexford County Council 2005).

Insurance claims filed in the aftermath of this event added up to €38m (Insurance Institute of Ireland, pers. comm. June 2018), while Munich RE Reinsurance Company (pers. comm. May 2018) estimated the overall cost of the event to be €51.1m.

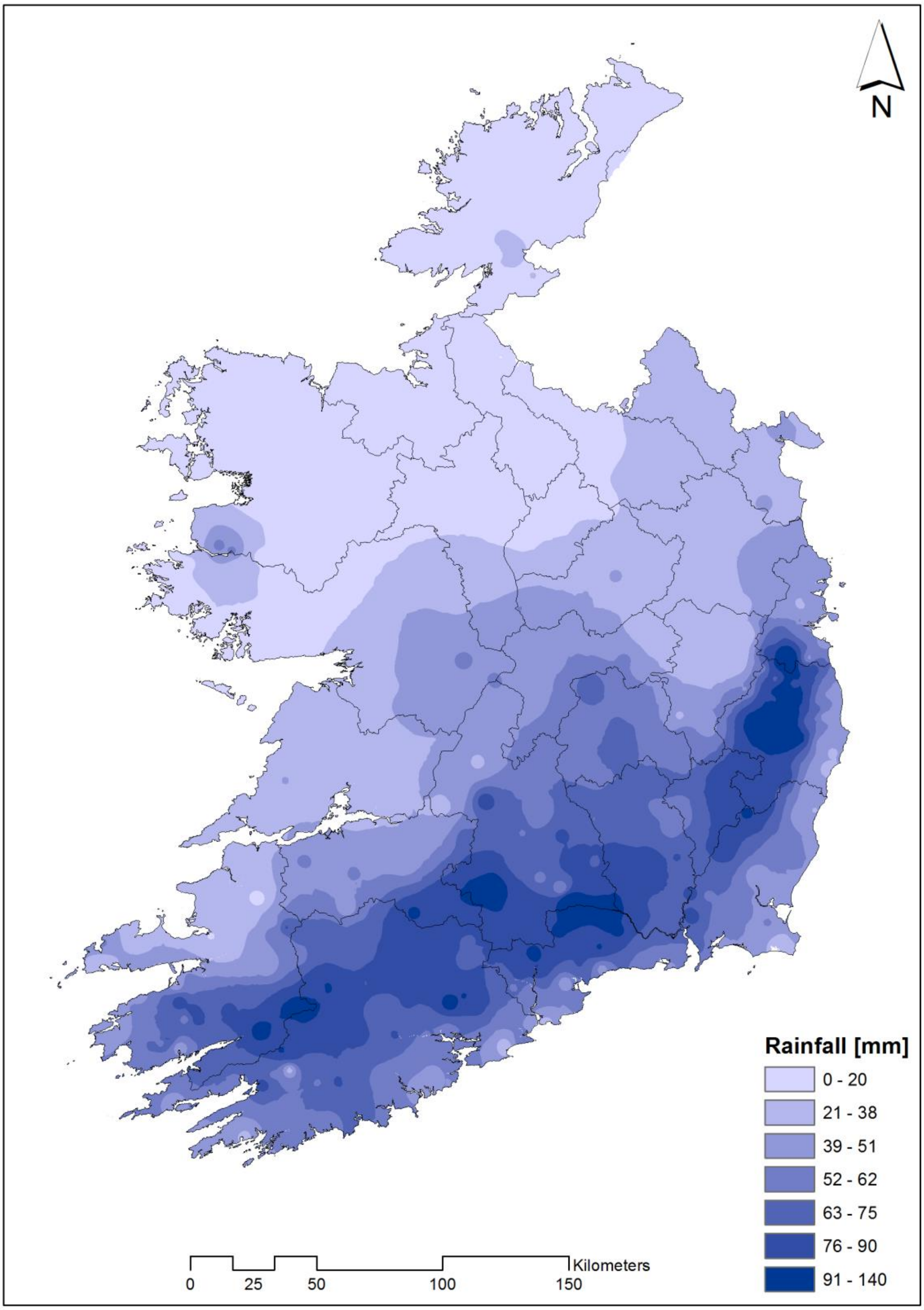

Fig 5. 48-hour rainfall map showing the intensity and distribution of precipitation produced by the storm of October 27/28th 2004.

4.6 2005, January 7/8th Storm Edwin (Gudrun)

TYPE OF EVENT: Storm/ Flood

RETURN PERIOD: N/A

EXTENT: Countrywide

IMPACTS: Widespread flooding in the west and in Dublin.

DAMAGES: €45.1m overall unadjusted (€51.6m CPI adjusted January 2018), including €29m insured unadjusted (€33.1m CPI adjusted January 2018).

FATALITIES: 0

EVENT NARRATIVE: Severe Atlantic storm evolved from a low pressure system south of NewFoundland and quickly travelled across the Atlantic to hit Ireland on January 7/8th 2005. West coast and Dublin area worst affected with sustained storm-force winds and hurricane-force gusts. 48-hour rainfall totals between 30 and 50mm in much of the country bar the southeast.

KEYWORDS: Storm, gale, flooding, flood.

Meteorological profile

The storm originated as a low pressure system south of NewFoundland, Canada on January 6th 2005. It quickly gathered strength as it travelled across the Atlantic and it moved over Ireland on the night of the 7th having an approximate minimum central pressure of 960hPa (Harwood 2012b). The bulk of the rain fell on the 7th but the 8th was still a very wet day bringing up the 48-hour totals to between 30 and 50mm in most places except the South and East of the country. On the 7th gales blew on the West and East coasts with near gale-force winds elsewhere. The winds intensified on the 8th and the recorded 10 min sustained winds reached storm force in Dublin and on the West coast with hurricane force gusts recorded at Mace Head, Co. Galway. Spatial distribution of the 48hour rainfall (ending 9am January 9th), and wind peak-strength and direction are illustrated in figure 6.

Impacts

Severe flooding in the western half of Ireland (Met Éireann 2005) and in Dublin were the river Tolka has burst its banks (EPA 2005). The overall losses stemming from this event were estimated by the Munich Re company (pers. comm. May 2018) to be €45.1m with an insured component of €29m.

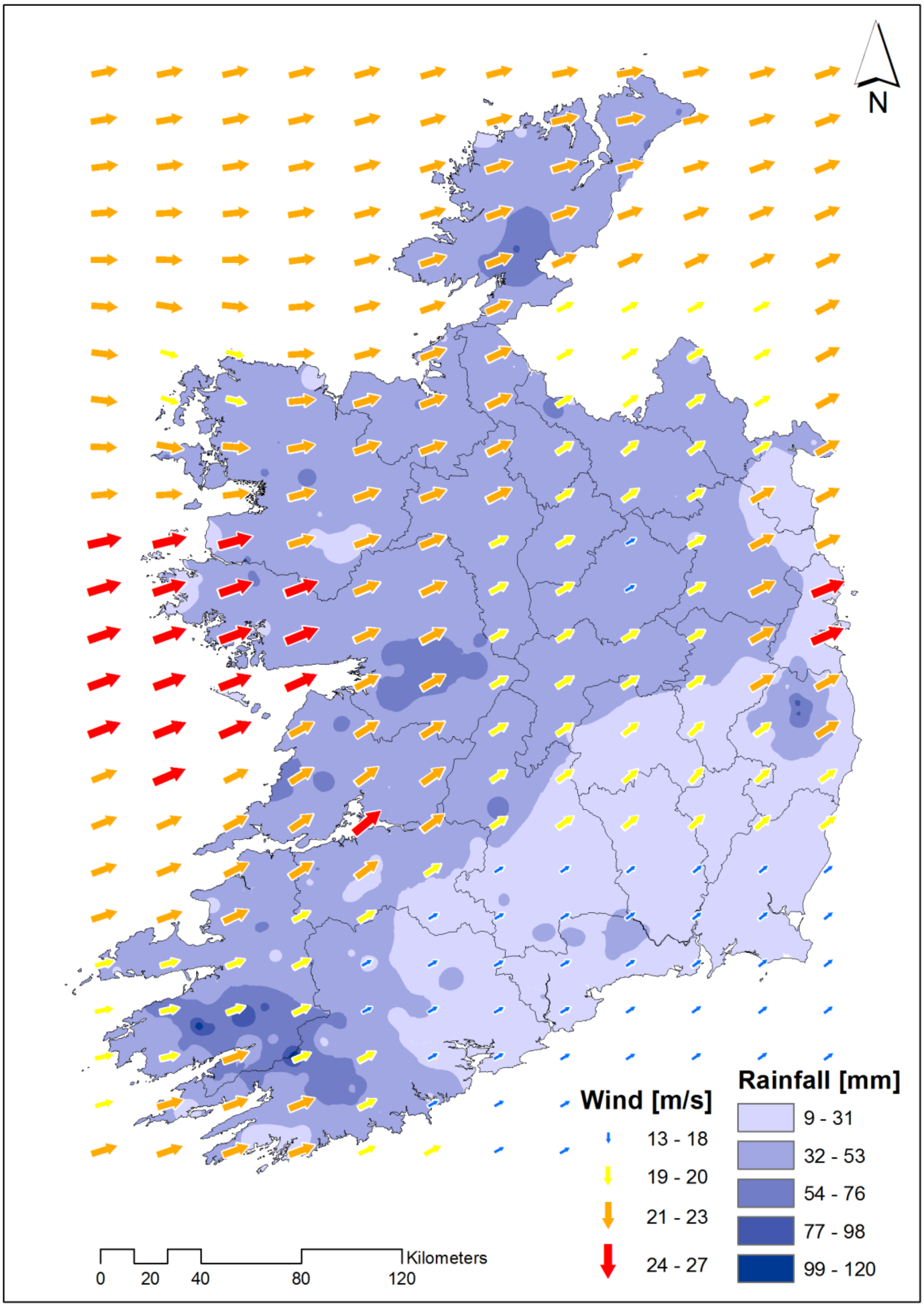

Fig 6. Distribution of 48-hour rainfall ending 9am January 9th and maximum 10 minute sustained winds at the height of the storm on January 8th.

4.7 2008, August floods

TYPE OF EVENT: Flooding/ Flash Flooding

RETURN PERIOD: up to 645 years for short-lived extreme rainfall

EXTENT: Countrywide

IMPACTS: Widespread traffic disruptions including rail and ferry services due to flooding, road closures, mud slides and fallen trees. Hundreds of businesses and homes inundated and evacuations of some residents. Freshwater supply locally compromised and boil notices issued in several counties; fresh water delivered to thousands of households. Crops lost in waterlogged land inaccessible to farm machinery. One report of drowning in River Fergus in Ennis, Co. Clare.

DAMAGES: €149.3m unadjusted (€145.6m CPI adjusted January 2018), including €96m insured unadjusted (€93.6m CPI adjusted January 2018).

FATALITIES: 1

EVENT NARRATIVE: Series of low pressure systems brought frequent and intense rainfall throughout the summer, making it the wettest on record for many stations across Ireland, with seasonal totals in excess of 200% of LTA in the East and Southeast. Persistent rainfall was interspersed with short-lived extreme downpours resulting in some stations recording their highest summer daily maximums. The soils' capacity to absorb rain was exhausted early in the season and intense rainfall in August led to frequent and widespread flash floods.

KEYWORDS: Rainfall, flood, flooding, flash flood.

Meteorological situation

The summer (JJA) of 2008 was the wettest on record across much of Ireland, the spatial distribution of its total rainfall is illustrated in figure 7. It also set new summer daily maximum records for several stations, including Shannon Airport where the records span 63 years. In the East and Southeast the summer totals were highest and equalled in excess of 200% of the 1961 - 1990 LTA, while most of the rest of the country received between 150- 200% of its normal rainfall. Even the least affected part of the country (Cos. Donegal, Sligo and Leitrim) still experienced a wetter than average summer. The unusually high number of rainy days (≥0.2mm of rain) throughout the season, kept the soils saturated especially in July and August. Most of the rainfall was caused by slow-moving low pressure systems, and while the summer was extremely wet, it was not unusual. The climate change models show a 10 - 15% decrease in summer rainfall for Ireland over the next four decades, while at the same time a warming atmosphere will likely make intense rainfall events more frequent. The occurrence of this event is not attributed to climate change (Lennon and Walsh 2008).

Introduction

Soils kept at or near saturation during most of the summer contributed to flash floods during recurring periods of intense rainfall throughout Ireland. During August of 2008 some degree of flooding occurred in most parts of Ireland, causing mudslides, widespread traffic disruptions and train and ferry service suspensions. Hundreds of business and residential properties sustained damages, some residents had to be evacuated from their homes, and fresh water had to be delivered to thousands of dwellings and boil notices were issued in parts of the country. Many sporting events were cancelled. Unfortunately, one fatality was recorded as a man drowned in River Fergus in Ennis (Irish Independent 2014, RTÉ 2008e and 2008f). Thousands of hectares of crops were lost as the farm machinery could not operate in waterlogged land (Irish Independent 2014). Flood related insurance claims in August 2008 were estimated by the Insurance Institute of Ireland (pers. comm. June 2018) to be €96m, and the overall value losses from this event including uninsured property and infrastructure damage is likely to be much higher. Below are accounts of four most damaging instances of flooding in August 2008, however these are by no means the only flooding events that month as many more localized and less significant events occurred throughout the month and in many parts of the country.

August 1st

One of the most severe floods of August 2008 occurred on the first day of the month in Newcastle West, Co. Limerick. Wet weather in days leading up to this event resulted in saturated soils and so the ground was unable to absorb huge quantities of rainfall intensified by the water running off the nearby steep hills (Lennon and Walsh 2008, Limerick County Council 2008a). Analysis of the rain gauges in the River Galey area revealed an average 24-hour rainfall (9am July 31st to 9am August 1st) of 85.9mm. The most intense rainfall occurred between 7.30pm on July 31st and 1am on August 1st (Limerick County Council 2008a). Assuming that all the recorded rainfall fell within a 5.25-hour period on the night of July 31st, the return period calculated for this storm was 645 years; although the same rainfall distributed over 24.5 hours produced a return period of 34 years (Limerick County Council, 2008b). The heavy rainfall was caused by a slow-moving occlusion associated with a depression passing to the north of Ireland (Lennon and Walsh 2008).

Some 200 properties suffered damage in this event, a number of people were rescued from their properties and vehicles though no injuries were reported, road closures due to inundation and landslides occurred, electricity and water supplies affected. Parts of the town inundated to 1.8m over the road level (Limerick County Council, 2008a).

Mallow was also badly hit by flash flooding on the afternoon of August 1st as River Blackwater overflowed its banks (Ireland Aerial Photography 2019, Independent.ie 2008). A bus was caught and stranded in the floodwaters, all its 50 passengers had to be rescued by boat (Ireland Aerial Photography 2019). Dozens of businesses were inundated (Irish Independent 2014). Due to traffic diversions the Gardaí warned motorists of significant delays and advised to best avoid the town and choose alternative routes (An Garda Síochána, 2008).

August 9-10th

As a cold front and an associated unstable airmass behind it tracked east across Ireland on August 9th, the eastern part of the country experienced some lightning and moderate (6 - 8mm) rainfall in the early morning hours. This morning rain was sufficient to exhaust the soil's absorption capacity and set the scene for the following event. A convective storm developed over the Midland Counties later in the day and a major precipitation event occurred between 3pm and 8pm, bringing record breaking rain to the Dublin area. The daily total of 76.2mm recorded at Dublin Airport that day was the station's new record August daily rainfall, exceeding the previous record recorded during the Hurricane Charlie in 1986 by 3mm; and the second-highest daily total overall. The return period for the 24-hour event was 43 years, while for the most intense 5-hour window of rain (3pm - 8pm) it was 237 years. Other areas of Dublin reported return periods of up to 104 years for the 24-hour period and well in excess of 250 years for the 5-hour event (Lennon and Walsh 2008).

In Dublin, sections of many major roads were closed including N3, N4, M1 and M50 (OPW 2008). Dublin City Council activated the emergency plan and pumps, sandbags and emergency crews were deployed in many areas of the city to fight the floodwaters (OPW 2008, Irish Examiner 2008). Motorists had to be rescued from stranded vehicles, of which one was reported to be swept down the road in the floodwaters; hundreds of houses were damaged (Irish Examiner 2008). Some rail services, including south and northbound DART connections were suspended (RTÉ 2008a). A soccer game scheduled for 7pm at Tolka Park was cancelled and so was the Tullamore Agricultural Show (RTÉ 2008a, Irish Examiner 2008). Outside of the capital flooding occurred also in Counties Kildare, Laois, Meath and Wicklow affecting many roads and a few properties. In Celbridge, Co. Kildare the sewage overflowed and spilled into the streets. Gardaí warned the motorists about diversions and subsequent delays (RTÉ 2008a and 2008b, Irish Examiner 2008).

August 11-13th

Although not as extreme as on August 9th, intense rainfall continued on the 11th, 12th and 13th of the month, resulting in more flash-floods across the country. The rainfall, while affecting most of Ireland, was more intense in the East on the 11th and 12th while on the 13th the Northwest was worst battered with daily falls of over 50mm in Counties Mayo, Leitrim and Galway.

Train service between Drogheda and Dundalk was substituted with a bus due to flooding, some DART services were also temporarily suspended (Irish Times 2008, RTÉ 2008d). Hundreds of houses in the north part of Dublin were flooded and the city centre also experienced localized flooding (Irish Times 2008, RTÉ 2008d). Many roads in Counties Kerry, Sligo, Leitrim, Meath, Donegal, Louth and Dublin were impassable due to flooding and some due to fallen trees. In Dublin road closures were widespread and included major roads such as M50 and N3 (Irish Times 2008, RTÉ 2008c and 2008d). One fatality was recorded in this event- a man drowned in the River Fergus in Ennis (RTÉ 2008e and 2008f).

August 15-18th

There was hardly any let up before the heavy rain returned on the 15th and 16th of August. The Midlands and East of Ireland were worst affected in terms of both rainfall and flooding. Several stations in Co. Offaly experienced in excess of 70mm of rainfall over the 48-hour period ending 12am on August 17th. On August 16th there were falls in excess of 40mm in several counties; Co. Meath (Dunsany) recorded 41.2mm, Co. Westmeath (Mullingar) 48mm and Co. Carlow (Oak Park) 47.7mm of rain in 24hr period ending 12am August 17th.

Road closures and traffic disruptions occurred in Cos. Kildare, Galway, Wicklow, Tipperary, Monaghan and Waterford, while Dublin escaped largely unscathed (RTÉ 2008g). Boil notices were issued in counties Sligo and Meath (RTÉ 2008h). The worst affected was by far Co. Carlow where River Barrow burst its banks inundating the city to depths of up to 1.5meters. Many businesses in the town were badly flooded and some residents had to evacuate their homes. Over one hundred people had to avail of alternative accommodation as the floodwaters threatened apartment complexes on Centaur Street, *nota bene*, only recently built (Pender 2008).

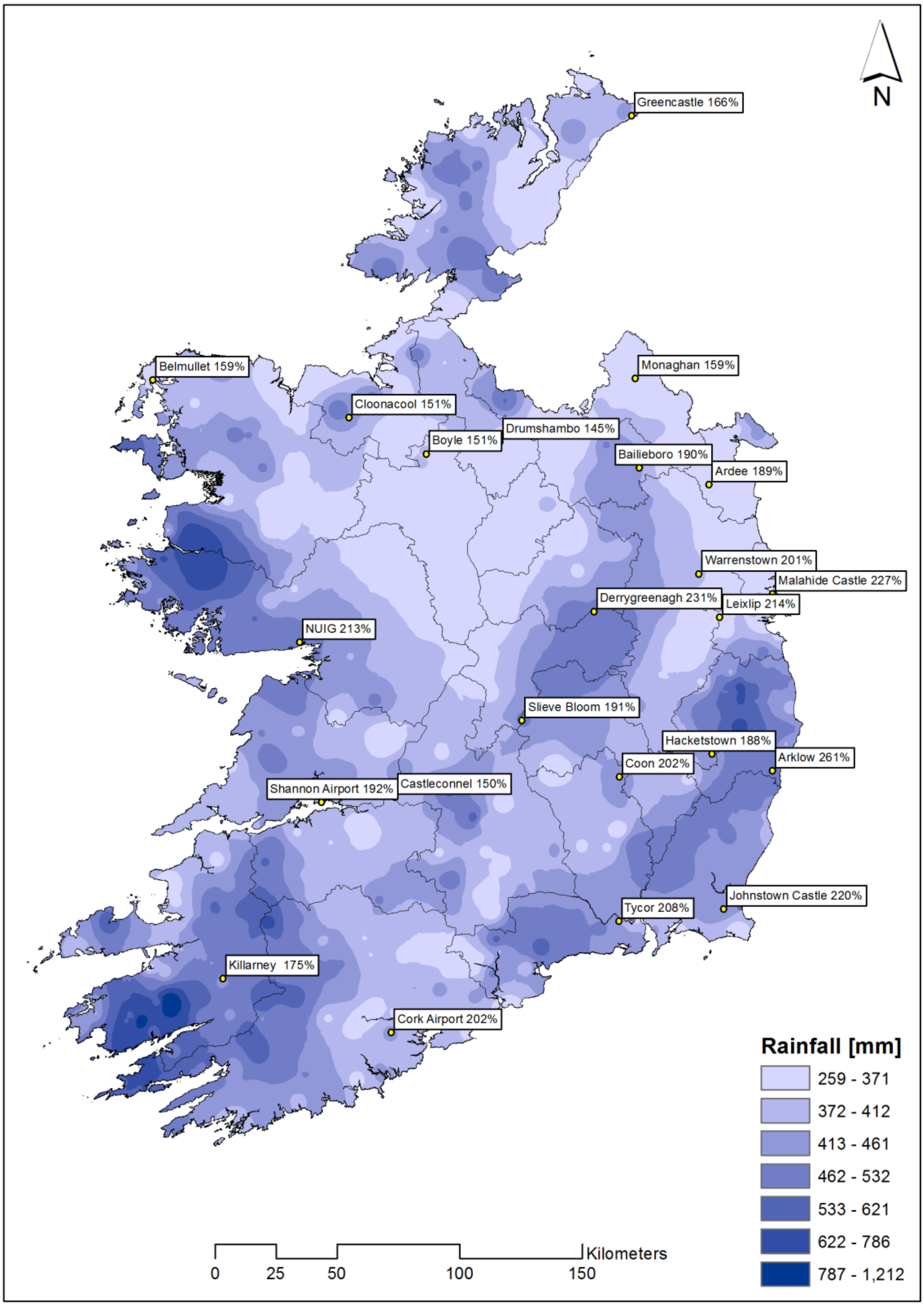

Fig 7. Summer 2008 rainfall distribution map also showing rainfall totals as percentage of the 1961 - 1990 LTA at selected weather stations.

4.8 2009, January freeze

TYPE OF EVENT:	Cold Spell/ Winter Damage
RETURN PERIOD:	N/A
EXTENT:	Countrywide
IMPACTS:	N/A
DAMAGES:	€47.6m unadjusted (€48.2m CPI adjusted January 2018), including €40m insured unadjusted (€40.5m CPI adjusted January 2018)
FATALITIES:	0
EVENT NARRATIVE:	Very cold first week of January thanks to an anticyclone descended upon Ireland from the north. Monthly mean temperatures mostly -0.2 to -0.4°C below their 1961 - 1990 average. Some snow and sleet later in the month. Most inland stations recorded >20 days with ground frost.
KEYWORDS:	Freeze, cold spell, winter damage.

Meteorological situation

Mean monthly temperatures were below normal across the country (mostly -0.2 to -0.4^{o}C below 1961 - 1990 LTA; see figure 8) except for the north and the southwest where they were slightly above average. The beginning of the month was the coldest with most of the lowest air temperatures recorded on or around the 7th, thanks to an area of high pressure which descended upon Ireland. There were snow and sleet between the 17th and the 25th and most inland areas reported over 20 days with ground frost (Met Éireann 2009).

Impacts

Munich RE (pers. comm. May 2018) estimated the overall losses from this cold spell to be €47.6m, while the Insurance Institute of Ireland (pers. comm. June 2018) reported that €40m of those damages were insured.

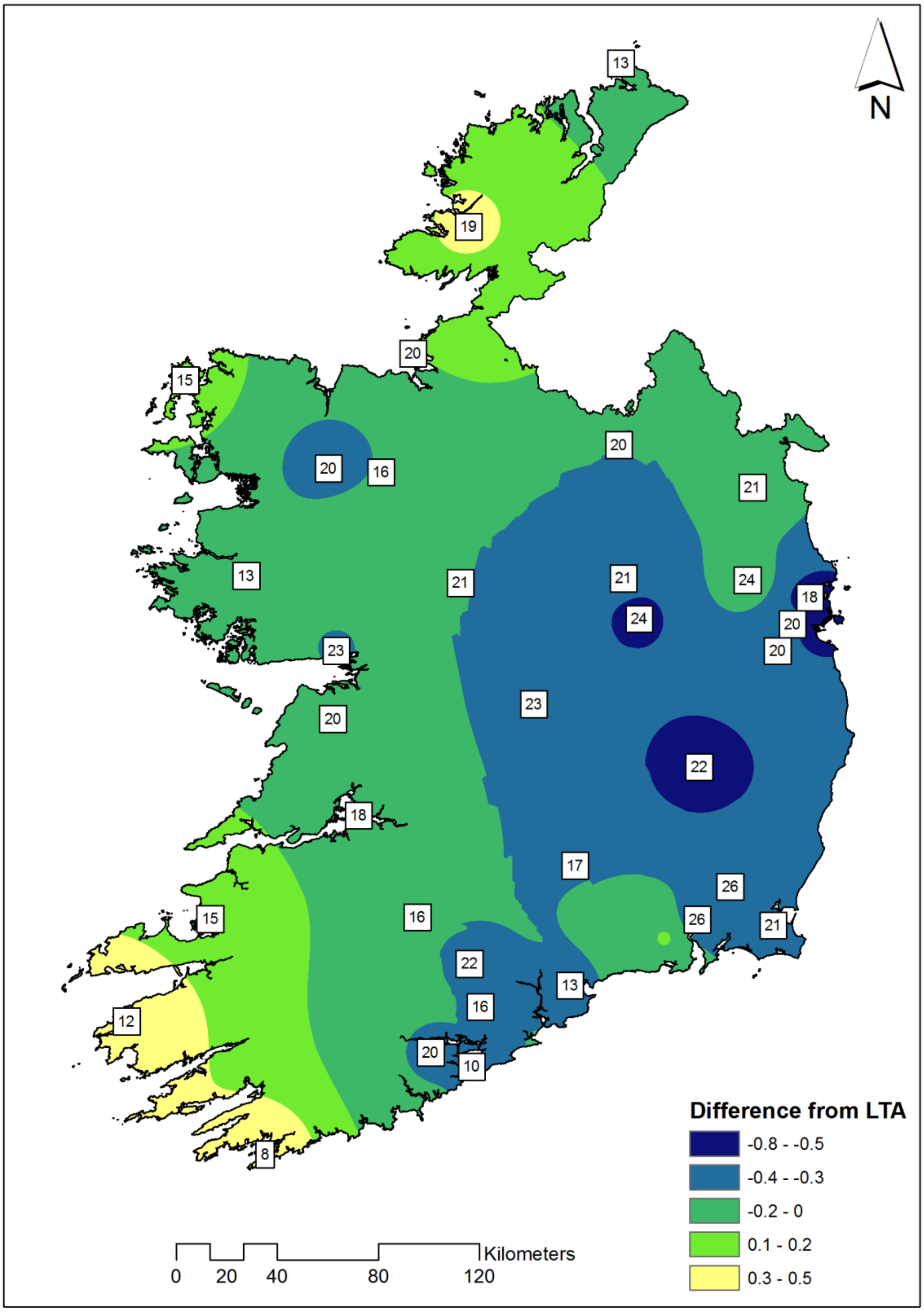

Fig 8. Mean monthly temperature map for January 2009, showing difference from 1961 - 1990 LTA. Values on the map (in °C) represent the number of days with ground frost at a given location.

4.9 2009, November 19th flooding

TYPE OF EVENT: Flood

RETURN PERIOD: Up to and over 500 years in the Shannon catchment

EXTENT: Countrywide

IMPACTS: One of the costliest weather disasters in Irish history. Hundreds of roads impassable, bridges threatened, rail and bus services cancelled. Homes and businesses flooded, many schools closed. Hundreds of people evacuated and rescued. Thousands without water supply and boil notices issued throughout the country. Counties Cork, Galway and Clare worst affected.

DAMAGES: €366m unadjusted, (€378m CPI adjusted January 2018), including €244m insured unadjusted, (€252m CPI adjusted January 2018).

FATALITIES: 0

EVENT NARRATIVE: An unusually wet summer followed by a wet autumn and the wettest November on record lead to a severe and prolonged flooding. The 48-hour deluge beginning on November 18th was the trigger point for this event. Already saturated soils and rivers and lakes at their capacity could not absorb any more water. Major rivers bursting their banks contributing to the extent of the disaster. Iniscarra (river Lee) and Parteen (Shannon) dams were threatened and hence forced to quickly release huge quantities of water exacerbating flooding downstream, which was especially catastrophic for Cork City.

KEYWORDS: Flood, flooding, rainfall, deluge.

Meteorological profile

The summer of 2009 was a third consecutive summer with above-average rainfall during all three summer months (JJA). Moreover, 2009 summer was the wettest of the three with a seasonal rainfall total of 620mm at Valentia Observatory, Co. Kerry, breaking the station's previous record by over 150mm (Hickey 2010). Although some let up came in September and early October, the soils remained largely saturated and river and lake levels high before the unsettled and extremely wet November (see figure 9) which eventually led to one of the costliest Irish weather disaster to date (Hickey 2010, Walsh 2010).

Cloone Lake, Co. Kerry recorded both the highest 24-hour rainfall (November 18th) and the highest monthly total, with 119mm and 649mm respectively. Monthly totals were above the 1961 - 1990 LTA in all of Ireland, and many midland areas received between 250% and 350% of that average. Countrywide, 292 out of 370 (79%) rainfall stations with significant records (>10 years) reported their wettest November yet (Walsh 2010). Valentia Observatory reported its highest monthly rainfall of any month since the station opened in 1866; it's total was 345.4mm of rain which equals 235% of its November average (Hickey 2010).

The rain returned in the second half of October, brought by a series of mid-latitude depressions and their active frontal systems passing across Ireland. This weather pattern only intensified during November, while the soil's ability to soak up water was already exhausted after the summer (NDFEM 2011, Walsh 2010). Several significant precipitation days occurred during late October and it rained on most November days, however, it was the persistent downpour which commenced on November 18th which triggered flooding. Torrential rain began on November 18th and lasted some 48 hours, interestingly, it was not associated with an Atlantic depression. The west and south of Ireland were particularly badly affected, and many stations there experienced 2-day accumulations in excess of 100mm of water. Relentless rain, fully saturated ground and exhausted capacity of rivers and lakes finally led to major flooding on November 19th (Hickey 2010). Return periods for the 24-hour rainfall on November 18/19th were highest in the southwest with some areas experiencing one in a 30 - 50 years event. Though the values were much higher for longer events, for example an 8-day rainfall ending on November 20th produced a 1 in a 100 - 200 years event across much of Cos. Clare, Galway and Roscommon, while a 25-day event ending on November 26th produced return period values in excess of 500 years in much of western Ireland (Walsh 2010).

Impacts

Few places in Ireland escaped the flooding and the damages were severe and widespread. The South and the West of Ireland were the worst hit by this event, but the Midlands and the Eastern counties were also affected. Hundreds of roads were impassable throughout the country and many bridges threatened, disrupting traffic and public transport. Home and businesses were flooded across Ireland and the economic output of the country was reduced. The flooding has also exposed the problem of developments on the floodplains for which the planning permissions were carelessly granted during the Celtic Tiger era, as many of them were badly inundated in this event (Hickey 2010). Many schools were temporarily closed and hundreds of people had to be evacuated from their homes, including all the residents of a nursing home in Ennis, Co. Clare where the river Fergus burst its banks. Boil notices were issued across the country due to the contamination of water treatment facilities, in Cork 18,000 homes had the water supply cut off. Vast amounts of agricultural land were inundated and the many late potato crops were lost, yet there were no reports of loss of livestock (NDFEM 2011). The military was deployed to help at multiple locations, i.e. Clonmel, Co. Tipperary where the city was badly flooded despite the partially completed flood defence works (Hickey 2010).

The overall nominal value of losses sustained during the November 2009 flooding was €366m, at the time making it the costliest weather disaster in the history of Ireland (Munich Re, pers. comm. May 2018). The insured fraction of the damages added up to €244m, of which 58% (€141m) resulted from claims filed in Co. Cork, making it by far the most impacted county. County Galway had the second highest share of insured damages with 9% (€23m) and Co. Clare placed third with 7% (€16m) of the total insured damages (Hickey 2010).

The county of Galway was among the first places to report flooding on November 18th and also among the worst hit countrywide (Hickey 2010, NDFEM 2011). Approximately 55% of Co. Galway's area was affected in this event (NDFEM 2011). Ballinasloe and Gort were among the worst affected towns in the county where many had to be evacuated, boil notices were issued and the electricity supply was locally disconnected as a safety precaution. Meanwhile, largely thanks to the drainage provided by the river Corrib Galway City was relatively unscathed. At the same time, the city was cut-off from the rest of the country as all major roads and the railway to Galway were at one point impassable. Some roads remained flooded for several months and in parts of the county flooding remained unresolved until February 2010 (Hickey 2010).

Many towns in Co. Cork were flooded, including Bantry, Bandon, Clonakilty. Mallow which is usually affected by the river Blackwater was saved by the recently completed flood relief features, however Fermoy downstream had less luck and was partly under water (NDFEM 2011). Cork City was particularly badly hit by the flooding which was hugely exacerbated by the unprecedented amounts of water released upriver at the ESB operated Inniscarra Dam. At the height of the intense rainfall of November 18/19th, the river Lee catchment was receiving in excess of 800m^2 of water. A combination inaccurate forecast and insufficiently reduced water level at the dam prior to the event, led to the fear of the dam being over-topped, which in turn led to the decision to release the water at an unprecedented rate. The release began in the early morning of November 20th and due to lack of communication caught many residents and businesses by surprise. Many parts of the city were under at least 1m of water and the damages to property and infrastructure were extensive. Some significant buildings were badly inundated in this event including the County Hall, County Library and The Kingsley Hotel. A total of 29 buildings belonging to The University College Cork were affected, including a The Mardyke Arena, the brand new Western Gateway Building and The Glucksman Gallery where many works of art were destroyed by the floodwaters (Hickey 2010).

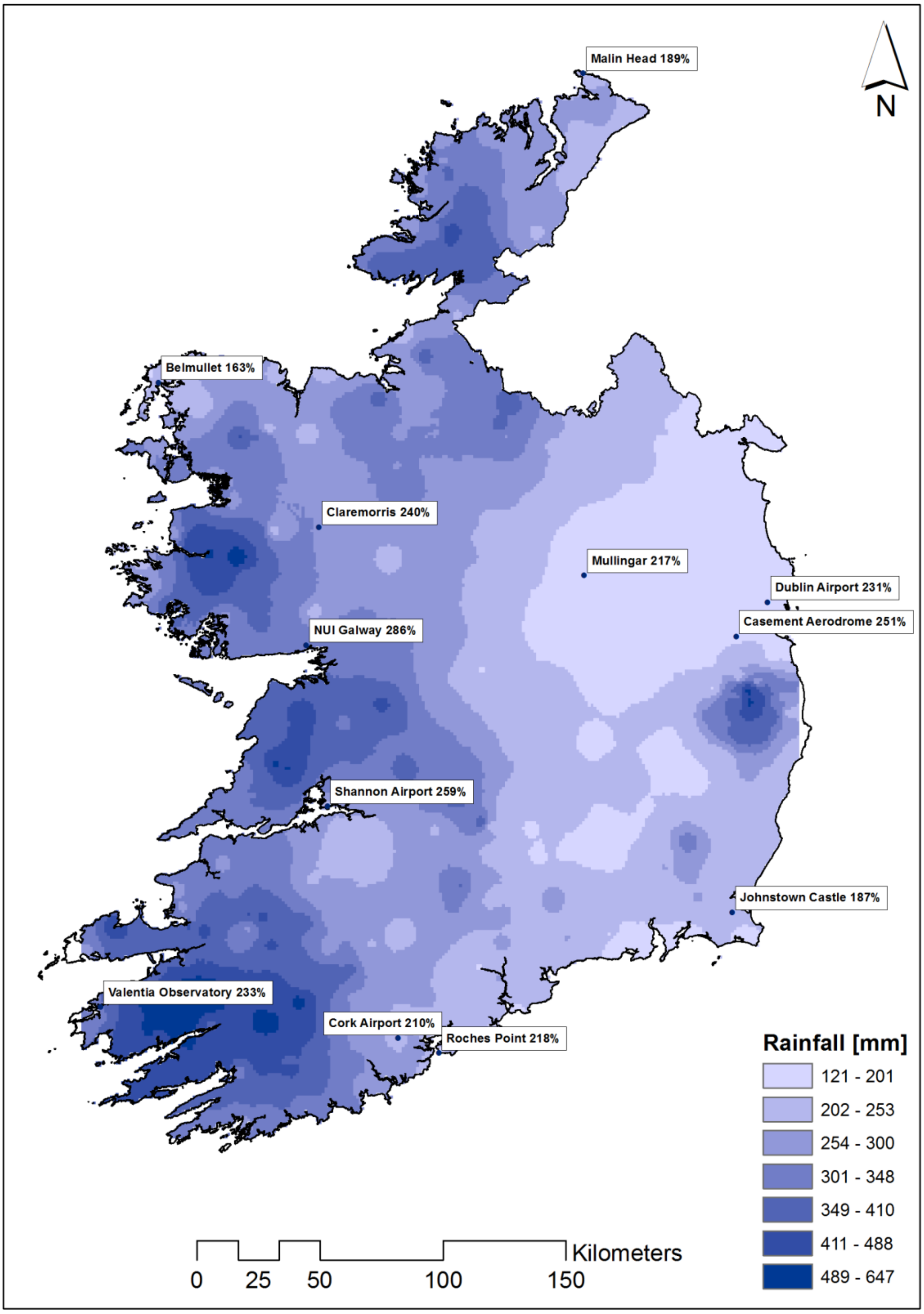

Fig 9. November 2009 rainfall totals also shown as percentage of LTA at selected Met Éireann weather stations.

4.10 2009/2010, December - February cold spell

TYPE OF EVENT:	Cold spell
RETURN PERIOD:	20 - 50 years for temperature 10 - 20 years for snow accumulations
EXTENT:	Countrywide
IMPACTS:	Thousands of injuries due to falls and car accidents (65% increase in treated fractures). Costliest Irish weather disaster to date, with bulk of the losses stemming from burst pipes. Traffic and public transportation disrupted, air traffic also affected by snowfall. Insufficient grit reserves and struggle to keep roads driveable. Schools temporarily closed. Strained water supply network and water rationing. Highest recorded demand for electricity and gas supply.
DAMAGES:	€372.7m unadjusted (€391.5m CPI adjusted January 2018), including €297m insured unadjusted (€312m CPI adjusted January 2018)
FATALITIES:	0
EVENT NARRATIVE:	Extremely cold winter with seasonal temperature averages around 2°C below the LTA, caused by a very negative AO phase. Close correlations between daily AO values and temperatures. Severest cold between December 25th and January 10th with temperatures some 6°C below normal. Several snow showers but no significant accumulations. Thaw in mid-January coincided with rainfall and lead to flooding especially in the south of Ireland.
KEYWORDS:	Cold spell, extreme cold, arctic oscillation, winter damage, snowfall.

Meteorological profile

Winter (DJF) 2009/10 was the coldest winter in Ireland since 1962/63 with mean seasonal temperature around 2°C below 1961 - 1990 LTA, and the mean of each month also below normal. The deepest cold during this spell occurred between December 25th and January 10th. The temperatures have then briefly recuperated before significantly dropping again in February (Met Éireann 2010). Below average temperatures continued until early May, even if their impact was no longer apparent (Hickey 2011). In the first ten days of January the average temperatures were 6°C below normal and it was during this period when most weather stations recorded their lowest air temperatures that season (figure 10). The record low air temperature that winter was recorded on January 7th at Mount Juliet, Co. Kilkenny at -16.3°C, which is only 2.5°C above the lowest temperature recorded in Ireland in the 20th century (Met Éireann 2018a, Hickey 2010).

The return period of this event in terms of temperature was 20 to 50 years under an unchanging climate, when factoring-in the warming trend of the climate, extreme cold spells in Ireland become much more rare (return period of 200 - 500 years). The return period for the snow accumulations was calculated to be between 10 and 20 years (Oldenborgh 2010).

Several snowfalls occurred but relatively high day time temperatures prevented significant accumulations, except at altitude. Days with ground-frosts were very frequent and in January they were twice as common as on average. The Valentia Observatory recorded almost 3 times its normal number of winter (DJF) days with ground-frost (Hickey 2010, Met Éireann 2010). Many ponds and lakes froze over solid during this time. In addition, thanks to the dominant high pressure, the winter was also unusually dry, calm and sunny (Hickey 2010).

Spells of cold weather lasting 10 days or longer are rare in Irish weather records, and significant snowfalls also rather rare in the last several decades. The severe winter of 2009/10 can be directly attributed to a particularly negative phase of the Arctic Oscillation (AO) and the northerly and north-westerly airflow it has caused to dominate over Ireland. The daily AO values are well reflected in the temperature trend throughout the cold spell, and the month of February had the lowest monthly mean AO value on record (-4.26). The area of high pressure firmly established over the Arctic resulted in the milder Atlantic weather being steered further south (Hickey 2011).

The thaw after the harshest part of the cold spell set in on January 11th as the Atlantic airflow began to influence the weather in Ireland again. However, milder conditions brought rain, which combined with the melting ice led to flooding, particularly in the south of the country (Hickey 2011).

Impacts

Luckily no direct fatalities were reported as a result of the cold, however the injuries from falls and car accidents were likely in the thousands. Health Service Executive (HSE) reported a 65% increase in fractures treated in Irish hospitals. Hickey (2011) also suggests an increased mortality rate, particularly among the elderly. Elsewhere in Europe this event had a significant death toll, 122 lives were lost in Poland and 22 more in the UK (Hickey 2010).

The mid-January thaw resulted in burst pipes in thousands of homes and businesses, which made up the bulk of the €297m in insured damages alone. Accounting for an estimated €200 - 300m lost due to reduced economic activity and the unreported and uninsured damages, the overall loss figure would be much higher (Hickey 2011). The cold winter of 2009/10 remains the costliest weather disaster in Ireland to-date, both in terms of insured and overall damage (Hickey, 2010, Munich Re, per. comm. May 17th 2018).

€10m was made available by the Department of the Environment Heritage and Local Government to cover the local authorities' costs of direct response (NDFEM 2011). Cork County Council alone has spent €6m on *ad hoc* repairs of the water supply network and numerous potholes resulting from the frequent freeze-thaw action (Hickey 2010). The usually maintained grit stocks were insufficient for the scale of the event and most local authorities quickly ran out of supplies, even though they were very selective and gritted only the most important roads. Grit had to be imported from abroad but this took time and resulted in untreated roads leading to more accidents (Hickey 2010).

Bus transport was disrupted everywhere and in Dublin all services were temporarily cancelled, the railway however was barely affected by the cold. The air traffic was also affected by the weather and Dublin Airport had to close on two occasions, many flights were delayed and some diverted to Shannon (Hickey 2010).
Many schools remained closed after Christmas recess and did not open again until mid-January.

All utility supply networks were strained. Frequent freezing and thawing lead to burst pipes and combined with many households leaving their taps running to prevent freezing resulted in a major depletion of the overall reserves and supply rationing. The demand on both gas and electricity supply was unprecedented (Hickey 2010).

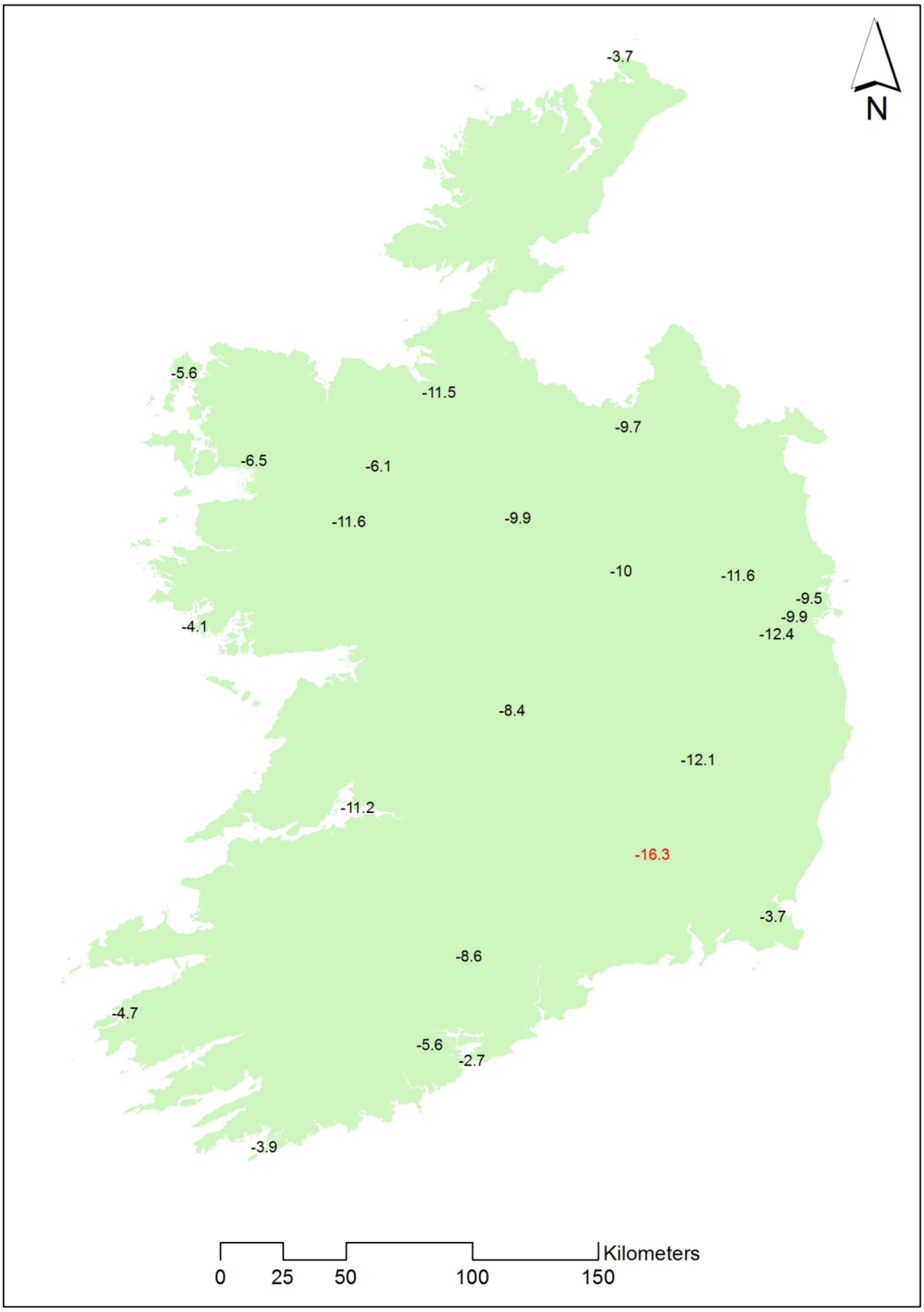

Fig 10. Lowest recorded temperatures (°C) during the extremely cold winter of 2009/10 at 24 weather stations in Ireland. The coldest temperature of -16.3°C was recorded at Mount Juliet, Co. Kilkenny on January 7th.

4.11 2010, November/December cold spell

TYPE OF EVENT: Cold spell/ snowfall

RETURN PERIOD: 50 years

EXTENT: Countrywide

IMPACTS: Event among the costliest weather extremes in recent Irish history. Disruptions to traffic though key roads largely kept passable throughout. Air traffic badly affected during the Christmas period. Burst pipes due to quick thawing made up the bulk of the insured damages incurred. Undetected leaks and people leaving the taps running depleted fresh water stocks to where they had to be rationed.

DAMAGES: €269m unadjusted (€280m CPI adjusted January 2018), including €224m insured unadjusted (€231.7m CPI adjusted January 2018).

FATALITIES: ≥5

EVENT NARRATIVE: Extremely cold end of November and December 2010 caused by a negative phase of the Arctic Oscillation and the resulting northwesterly airflow over Ireland. This event ranks among the six severest cold spells and the three biggest snowfall events in recent Irish history. Coldest December on record for many stations; records broken for the lowest ever daytime temperature and lowest ever monthly mean temperature for any month.

KEYWORDS: Cold spell, extreme cold, winter damage, snowfall.

Meteorological profile

Cold spells imply a prolonged period of significantly below-normal temperatures, but are not clearly defined in meteorological terms and hence cannot be easily compared (Hickey 2011, Met Éireann 2011a). Nonetheless, the cold period of November-December 2010 (here also referred to as winter 2010) was without a doubt among the most severe in recent Irish history. Although not the most persistent on record, it can be characterized as the coldest and also the earliest, since it began in November- outside of the meteorological winter. Additionally, it ranked among the top three biggest events in terms of snowfall (Met Éireann 2011a).

Historically, multiple causal factors were found responsible for extreme cold spells in the usually mild and maritime Irish climate and included the solar output, large scale volcanic activity or the Arctic Oscillation (AO). Recently, the loss of sea ice in the Arctic and the Anthropogenic Global Warming (AGW) were also considered as influencing factors. Typically however, it is a combination of any of the abovementioned factors and the variable weather patterns and it is often difficult to attribute a single cause to a particular event (Hickey 2011).

In the case of the 2010 winter, the cause was quite apparent in the heavily negative AO phase and its influence on the airflow over Ireland. The very low AO values recorded (especially in December), caused the northerly and northwesterly airflows to dominate over Ireland (Hickey 2011).

This cold spell had two distinct phases: November 27th to December 9th and December 17th to 26th, with a week-long interval during which the temperatures were somewhat higher, although still remained below average (Hickey 2011, Met Éireann 2011a).

Many records were broken during this event. Despite most of November being mild and warm, the severe cold at the end of the month brought the monthly mean temperatures low enough for many stations to report their coldest November since 1985. Dublin Airport and Casement Aerodrome synoptic stations recorded their coldest November temperatures yet, with -8.4^{o}C and -9.1^{o}C respectively.

December was the coldest month on record at some stations and some areas experienced 9 consecutive days of constant negative temperatures. Ballyhaise, Co. Cavan recorded an all-time lowest daily temperature for Ireland at -9.4ºC and its monthly average of -1.4ºC was the lowest ever for any month (Met Éireann 2011a). Records from the few stations in Ireland that measure snow depths have shown the greatest accumulation in the Dublin area and the east of Ireland (>20cm), the northwest experienced depths of 10 - 15cm, while the south and southwest were least affected with <10cm of snow (Met Éireann 2011a).

This cold spell has an approximate return period of 50 years which refers to the temperature only, no estimate is available for the snowfall (NDFEM 2011).

Impacts

The disruptions and damages caused by the cold winter of 2009/10 prompted revision and improvements in emergency response services which ultimately lead to a better management of the situation during the extreme cold of November and December of 2010. Although better managed, disruptions, damages and injuries still occurred. The severity of this event is well illustrated by the deployment of over 3400 military troops together with over 1000 hi-mobility army vehicles to provide assistance to the local authorities (NDFEM 2011).

Snowfall and formation of sleet caused disturbances to traffic. Although primary national roads and some key routes (i.e. access to hospitals and schools) were prioritized for salting and in general successfully kept open, rural and local roads were severely affected. All public transportation services including bus, luas and train services remained operational with minor disturbances and, overall, managed to carry out over 90% of their scheduled services. Some 200 snow-ploughs were clearing roads throughout the country. Insufficient salt stocks caused problems later during the cold and an *in promptu* salt import was necessary. A total of 104,000 tonnes of salt were used during this event to cover some 17,000km of prioritized road network (NDFEM 2011).

Perhaps most disruptions were caused to air traffic, especially during the busy

Christmas period. Although Shannon and Cork airports also endured some disturbances, Dublin Airport was most severely affected by intense snowfalls which lead to its closure on 6 separate occasions during November/December cold spell. Disruptions and delays to air traffic abroad also impacted on the Irish passengers travelling to and from home for Christmas (NDFEM 2011).

The overall nominal loss value of €269m (Munich Re, pers. comm. May 17th 2018) does not include the losses from stumped economic activity, which Hickey (2011) suggested to be at least €100m. The insured fraction of this estimate was 83% at €224m (Insurance Institute of Ireland, pers. comm. June 2018). There were 30,000 household claims which mostly related to burst pipes, commercial claims made up a much smaller portion of the overall insured losses (NDFEM 2011).
In the aftermath of the 2010 winter, the Department of the Environment, Heritage and Local Government made over €9m available to local authorities to cover the cost of the immediate response (NDFEM 2011). The losses from this extreme event place it among the costliest weather and climate extremes in the recent Irish history.

Water supply was affected particularly badly after December 26th, when the thaw and quick rise of temperatures from -10°C to 10°C caused some 25,000 separate leaks for the local authorities to deal with. Undetected leaks and people leaving their taps running to prevent freezing significantly depleted the reservoir levels (NDFEM 2011). Electricity supply and fuel distribution experienced minor disturbances but were largely successfully delivered to customers throughout the cold spell (NDFEM 2011). The key impact of the cold on agriculture was the unavailability of water for livestock. Some livestock was reported lost in attempts to get water from frozen lakes (NDFEM 2011).

At least 5 fatalities were recorded as a direct consequence of the cold, sustained injuries due to slips and car accidents were counted in thousands (Hickey 2011).

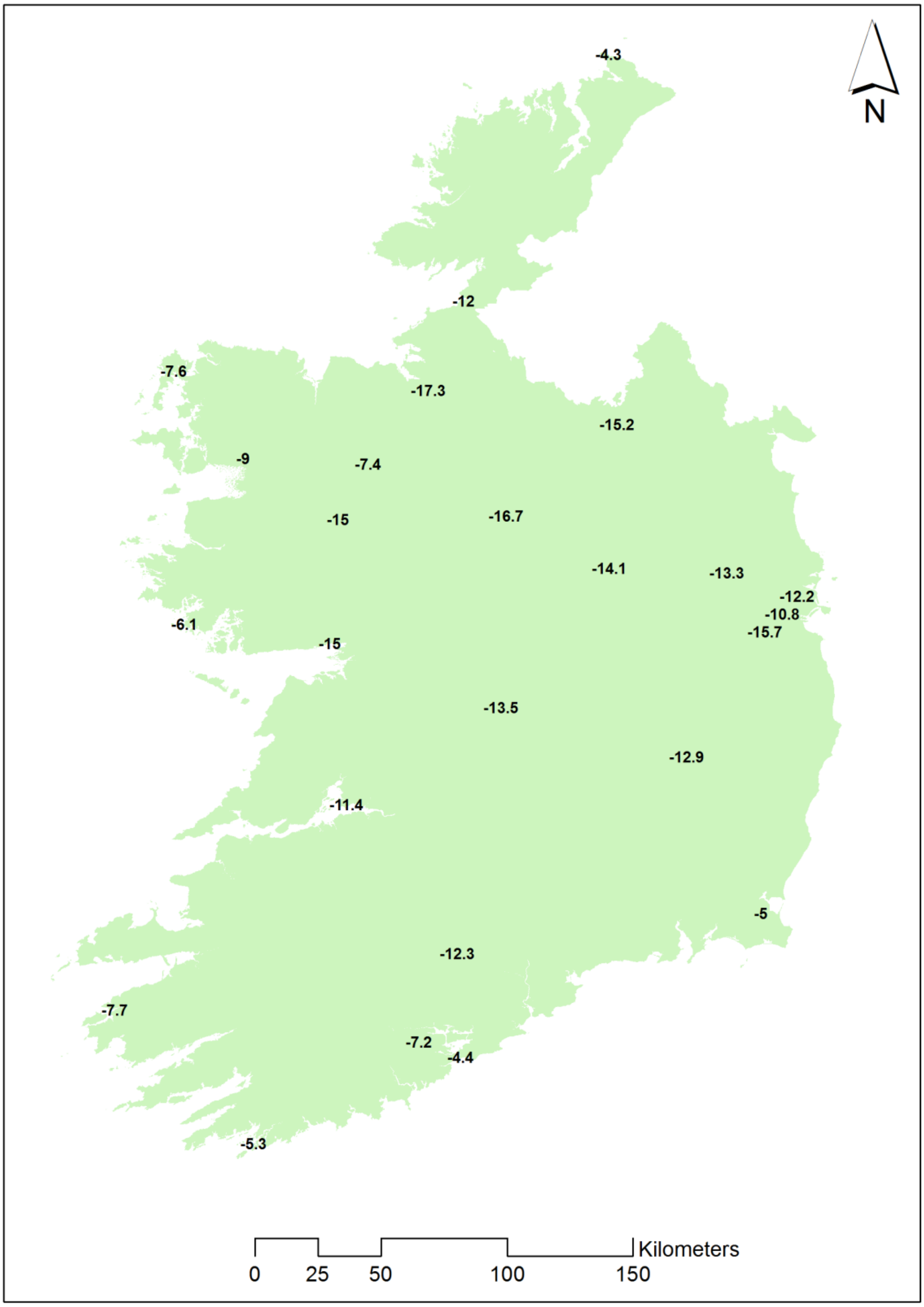

Fig 11. Lowest recorded temperatures (°C) during the cold spell of November/December 2010 at 25 weather stations in Ireland. Inland stations recorded lower temperatures than those located on the coast.

4.12 2011, October 24th extreme rainfall in Dublin/ Wicklow area

TYPE OF EVENT:	Rainfall/ flooding
RETURN PERIOD:	20 - 25 years for 24-hour rainfall 40 - 75 years for 12-hour rainfall 60 - 100 years for 9-hour rainfall 40 - 80 years for 4-hour rainfall
EXTENT:	Greater Dublin area and Co. Wicklow; other counties affected to a much lesser extent.
IMPACTS:	Local flooding in many places throughout Ireland but most significant in the greater Dublin area and Co. Wicklow. The resulting financial losses place it at No. 4 among the costliest weather extremes in recent Irish history. Major disruptions to all forms of land transportation as well as ferry connections and air traffic. Thousands of homes and businesses inundated.
DAMAGES:	€186.4m unadjusted (€187.7m CPI adjusted January 2018), including €127m insured unadjusted (€127.7m CPI adjusted January 2018).
FATALITIES:	2
EVENT NARRATIVE:	A slowly advancing frontal depression positioned over Ireland produced extreme rainfall in the eastern part of the country. The 9-hour totals in Dublin were not far from their usual monthly values for October and combined with the already saturated soils led to flooding in parts of Dublin and Wicklow.
KEYWORDS:	Extreme rainfall, rain, Dublin, flood, flooding.

Meteorological situation

The centre of an extensive and slow-moving frontal depression moved over Ireland on October 24th 2011 and led to a short-lived yet extremely heavy rainfall. The intensity of this event was enhanced by orographic lift provided by the Wicklow mountains and the already exhausted absorption capacity of the soil due to the significant rainfall on the previous day (Met Éireann 2011b). The 24-hour rainfall totals recorded at Dublin Airport and Casement Aerodrome weather stations roughly equalled the average totals for all of October (1981 - 2010 LTA) and had return periods of 20 - 25 years. It was the 9-hour totals however, for which the highest return periods were calculated (60 - 100 years); this is not surprising given that almost all of the rain recorded on October 24th fell within a 9-hour period (Met Éireann 2011b and 2018b). See figure 12 for the distribution of 48-hour rainfall ending 9am October 25th. The combination of torrential rain and already saturated soils lead to flooding in parts of Dublin and the east coast of Ireland (Met Éireann 2011b). A severe weather warning was issued by Met Éireann for Leinster and much of east coast (Mirror.co.uk 2011).

Impacts

A comparison of peak level and flow data from selected hydrometric stations operated by the EPA shows that the severity of the flooding of October 24th 2011 is comparable to that resulting from Hurricane Charlie in 1986 (Mac Cárthaigh 2011). Coast Guard and the Fire Brigade were overwhelmed by the number of incoming emergency calls and Dublin City Council activated its major emergency response plan (Met Éireann 2011b, The Irish Times 2011).

The flooding resulted in thousands of homes and businesses being inundated and significant traffic disruptions. Delays were experienced on major roads such as N81, M1, M7 and M50, parts of some of which were closed. LUAS, Dart and bus services (both city and commuter) were also affected and sometimes cancelled, as were ferry services both to and from Dublin (Met Éireann 2011b, Mirror.co.uk 2011, The Irish Times 2011). At Dublin Airport many flights were either cancelled or diverted to

Shannon (The Irish Times 2011, Met Éireann 2011b).
The river Dodder burst its banks and inundated Dundrum Town Centre shopping mall up to 10cm in depth, causing it to be evacuated and closed (Mirror.co.uk 2011, Hough 2011). Also in Dundrum, a number of stranded motorists were rescued by the Coast Guard. River Liffey and the Royal Canal also burst their banks (Mirror.co.uk 2011).

Sadly, two lives were lost as a direct result of this event, including a young Garda officer who was swept away by the floodwaters while directing traffic at Ballysmuttan Bridge, Co. Wicklow. A rescue operation involving local mountain rescue teams was attempted but ended unsuccessful (The Irish Times 2011, Met Éireann 2011b).

Some flooding occurred in counties Kerry, Waterford, Louth, Monaghan, Laois and Meath, but not to an extent comparable with that in Dublin and Wicklow (The Irish Times 2011).

Overall this event resulted in over €180m in damages, making it the fourth costliest weather related disaster in Ireland post-1980 (Munich Re, pers. comm. April 2017).

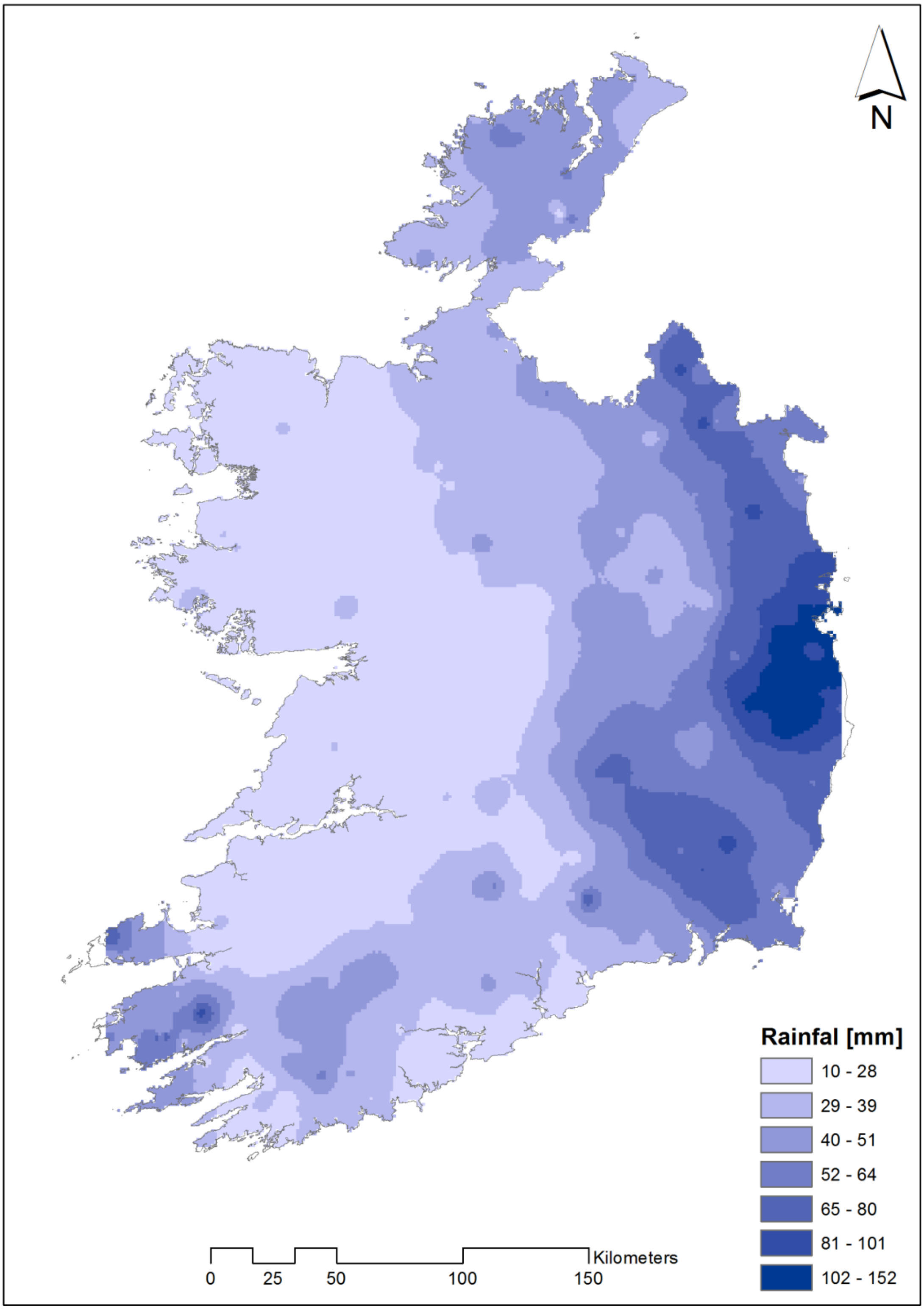

Fig 12. Distribution of the 48-hour rainfall ending 9am October 25th which lead up to the flooding.

4.13 2012, June 27/28th flooding

TYPE OF EVENT:	Flood
RETURN PERIOD:	N/A
EXTENT:	Severe in Cork County and City, minor incidents in other counties.
IMPACTS:	Cork bore the brunt of the damages; Clonakilty, Douglas and Glanmire were the worst affected areas with flood depths of up to 1.2 meters in places. Significant flooding also on the north side of the city, especially in Blackpool and Ballyvolane. Hundreds of properties were flooded as well as many roads and bridges. Electricity supply to approx. 10,000 customers was disrupted.
DAMAGES:	€72.5m unadjusted (€72.3m CPI adjusted January 2018), including €54m insured unadjusted (€53.8m CPI adjusted January 2018).
FATALITIES:	0
EVENT NARRATIVE:	Wettest June on record for all but two weather stations across Ireland; it was also significantly cooler and duller than average. The soil's capacity to absorb the rain was largely exhausted due to the persistent precipitation throughout the month. A convective storm swept over Ireland on the 27/28th and produced very heavy rainfall in Co. Cork in the early morning hours of the 28th. Falls of 30 - 50mm at many stations in the county, largely concentrated within a 3-hour period ending 3am.
KEYWORDS:	Rainfall, flood, flooding, flash flood.

Meteorological situation

June of 2012 was the wettest on record across Ireland (figure 13), except Dublin Airport and Phoenix Park. It was also significantly colder and duller than average (McGreevy 2012). Cork Airport and Roches Point weather stations recorded 343% and 428%, respectively, of their 1971 - 2000 averages.

A convective storm moving across Ireland on June 28th, produced rainfall totals of up to 50mm in Co. Cork. Rainfall across the rest of the country was mostly below 20mm (Cork County Council 2012). Although Co. Cork experienced days with higher daily rainfall earlier in the month, particularly on the 2nd, 7th, 14th and 15th, those did not result in significant flooding. Those events however, combined with lighter but persistent rainfall throughout the month, have exhausted the soil's capacity to absorb any more water and so enhanced the severity of the flooding of the 28th. Met Éireann office has issued advisory notices against heavy rain at 5am and again at 5:56am the previous day, warning about expected 30 - 50mm rainfall totals countrywide and possible 70mm totals locally. The actual rainfall varied across the country, Co. Cork was worst affected and many of its stations received between 30 and 50mm of rain as forecasted. Most of this rainfall was concentrated in a 3-hour period ending 3am (Cork County Council 2012).

Notably, the largest rivers in Co. Cork (Bandon, Blackwater, Ilen and Lee) usually responsible for major floods did not flood during this event. Instead, smaller streams and rivers burst in the steep catchments of Clonakilty, Douglas and Glanmire, making those areas the worst affected (Cork County Council 2012).

Impacts

Torrential rain and saturated soils resulted in flash flooding in the early morning hours of June 28th. In places the flooding was further enhanced by blockages and exhausted capacity of the drainage infrastructure. Areas most badly hit were Clonakilty, Douglas and Glanmire, with less significant flooding occurring also in Blackpool, Ballyvolane and several other locations across the city and county (Cork

County Council 2012, Cork City Council 2012). The bulk of the rain fell in a 3-hour period ending 3am resulting in immediate flash flooding. At 4:09am the Cork County Council Flood Emergency Response Plan was activated and notification was sent to the Crisis Management Team members about an emergency meeting scheduled for 7am in the County Hall (Cork County Council 2012).

Munster Regional Control Centre received 113 calls between midnight and 7am on June 28th, and mobilised various Fire Brigades to respond to 34 incidents. There was also a dedicated line set up by the Crisis Management Team, via which members of the public could report floods-related matters (Cork County Council 2012).

In Clonakilty most of the town centre flooded by 4am and the event as a whole was far worse than that of 2009. Parts of river banks collapsed, more than 70 residential and more than 100 businsess/public properties were flooded, including the Town Hall, fire station and a library. Further property inundations were reported in the nearby villages. There were 36 roads damaged in Clonakilty and its vicinity as well as 16 bridges, of which 4 to the point of being impassable. There was a welfare centre set up at the Quality Hotel to assist those who had to evacuate their houses (Cork County Council 2012). The maximum flood depth of this event was recorded at Connolly Street at 1.2 meters (OPW 2012a).

In Douglas, the Ballybrack stream has burst its banks between 1am and 2am upstream of Douglas Village, due to a trash screen blocked by debris carried by the swollen river. Up to 0.9m of water were reported in various locations. Some 12 houses and approximately 100 commercial premises were inundated as well as a Community Hall and a medical centre (Cork County Council 2012).

Flooding in Glanmire area also occurred in the early morning hours following heavy rain and the river Glashaboy overflowing its banks. Some 45 houses in the Meadowbrook Estate and 10 commercial units in the Hazelwood Shopping centre were inundated to depths of up to 1.2 meters. There was a lot of mud and debris left after the floodwaters receded in the early afternoon, the Council staff were also cleaning out gullies and screens blocked by debris. Glanmire Community Hall was operating as a welfare centre for those affected, dispensing warm beverages and food provided free of charge by the local traders (Cork County Council 2012).

Within the city, significant flooding occurred at a number of locations on the north side, especially in Blackpool and Ballyvolane where the flooding was caused by the overflow of rivers Bride and Glen respectively. Overall there were approximately 155 houses flooded on the north side of the city, of which up to 30 in Ballyvolane and 90 in Blackpool where a Church was also flooded (OPW 2012b). In Ballyvolane some homes had to be evacuated (BBC News 2012).

Other areas affected in the county, although to a much lesser degree, included Crookstown, Skibbereen, Dunmanway, Mallow, Carrigaline, Mitchelstown and Bandon (Cork County Council 2012). A number of roads were also reportedly flooded in counties Tipperary, Waterford, Westmeath, Galway, Limerick and Kildare (Barry 2012). Overall, approximately 10,000 ESB customers throughout the county had their electricity supply temporarily disrupted (Barry 2012).

The Insurance Institute of Ireland estimated the total cost of insurance claims from this event to be €54m (pers. comm. June 2018), while the overall cost of this event as estimated by Munich Re (pers. comm. May 2018) was €72.5m.

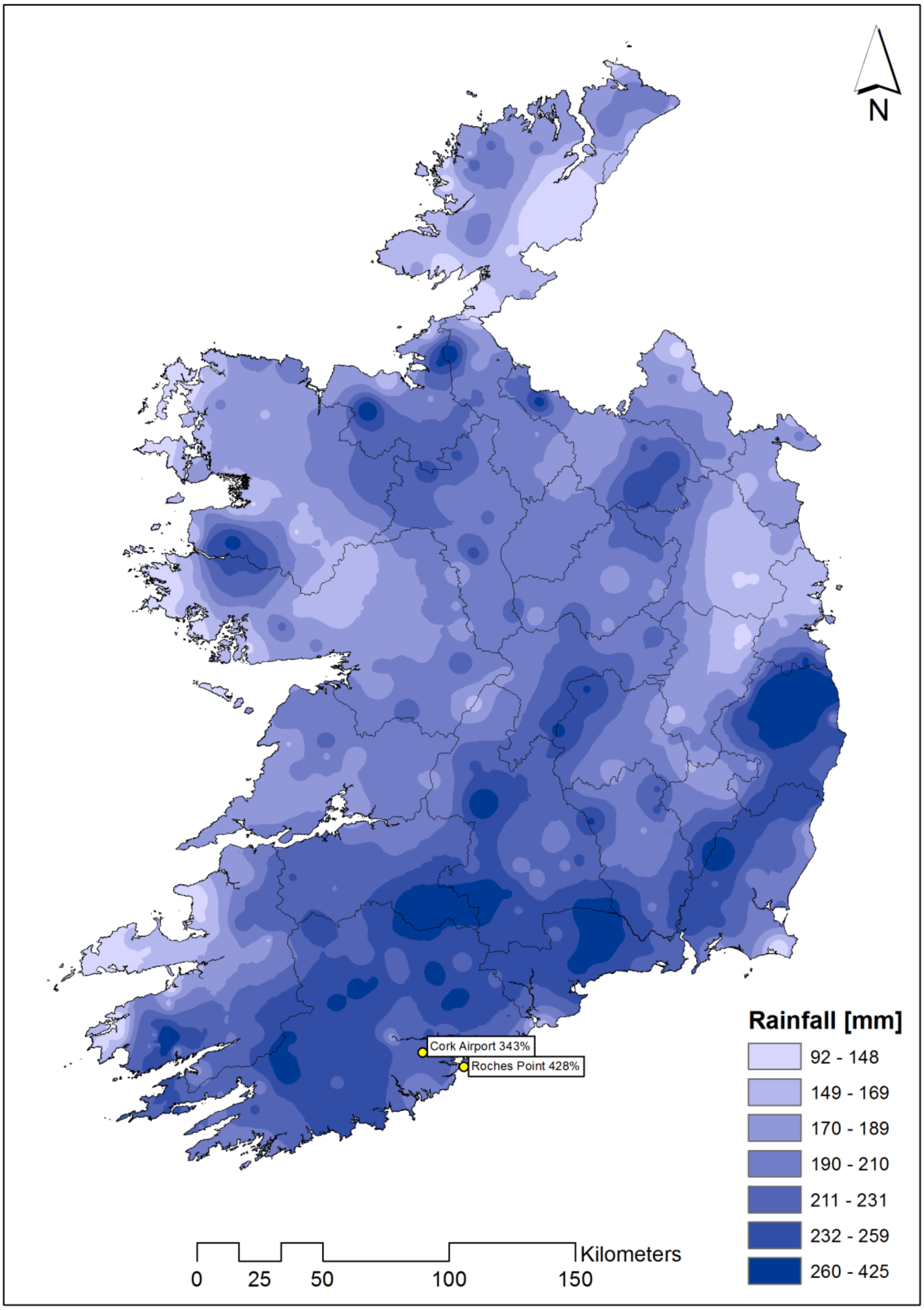

Fig 13. Rainfall distribution map showing total precipitation recorded in June 2012. Data utilized in this map is Met Éireann redistribution data from 472 rainfall station across Ireland. Marked on the map are Cork Airport and Roches Point weather stations which recorded 343% and 428% of their 1971 - 2000 LTA respectively.

4.14 2013, July 26th thunderstorm and flooding

TYPE OF EVENT:	Extreme rainfall/ Flooding
RETURN PERIOD:	N/A
EXTENT:	Countrywide
IMPACTS:	Localized flooding in Donegal, Dublin, Westmeath and Wicklow. Worst affected was Letterkenny General Hospital with several departments flooded to depths of up to 0.9m, resulting in hugely expensive losses and some evacuations of patients.
DAMAGES:	€97.9m unadjusted (€97m CPI adjusted January 2018), including €75.3m insured unadjusted (€74.6m CPI adjusted January 2018)
FATALITIES:	0
EVENT NARRATIVE:	Very heavy but highly localized showers throughout Ireland. Donegal and Dublin city worst affected with up to 35mm of rain over very short time.
KEYWORDS:	Extreme rainfall, flash flooding, flood.

Meteorological situation

Very heavy but highly localized showers at several locations throughout the country (see figure 14), worst in eastern Donegal and Dublin City (RTÉ 2013, OPW 2013). While there were falls in excess of 30mm in other parts of the county, Letterkenny area received between 10 and 15mm of rain. OPW (2013) report on the flooding of the Letterkenny General Hospital indicates its occurrence between 5pm and 6pm. Given the nature of this event (flash flood) it can be assumed with much likelihood that the rainfall immediately preceded the flooding. This would also be indicated by the data from the only two weather stations in Donegal which record precipitation hourly- Finner and Malin Head, which were affected by showery rain at 5pm and 8pm respectively.

Heavy showers occurred also in Dublin City; their highly localized nature is well illustrated by the difference in rainfall totals at stations located close to each other. While 35mm of rain were recorded at Merion Square, only 14.3mm were recorded at Glasnevin and less than 1mm at Dublin Airport, Casement Aerodrome and Phoenix Park.

Impacts

Flash flooding resulting from this extreme rainfall in Dublin, Westmeath and Wicklow was minor. Traffic disruptions due to road inundation was the most common impact. In Dublin the City Council offices at Wood Quay suffered some flooding as well (RTÉ 2013).

In Letterkenny, the General Hospital suffered immense damages as the river Glencar- Swilly's tributary, burst its banks. The river is culverted under the hospital's site and debris blocking a trash screen at one of the culverts caused it to overflow. Many buildings on the hospital's campus were inundated to between 0.2 and 0.9 meters, including the newly opened A&E Department (OPW 2013). Wards located on the ground floor of the hospital had to be evacuated and some patients were also transported to Sligo and Derry hospitals. The situation was declared an emergency and a crisis management team was put in place to deal with the event (RTÉ 2013, O'Connell 2013, OPW 2013).

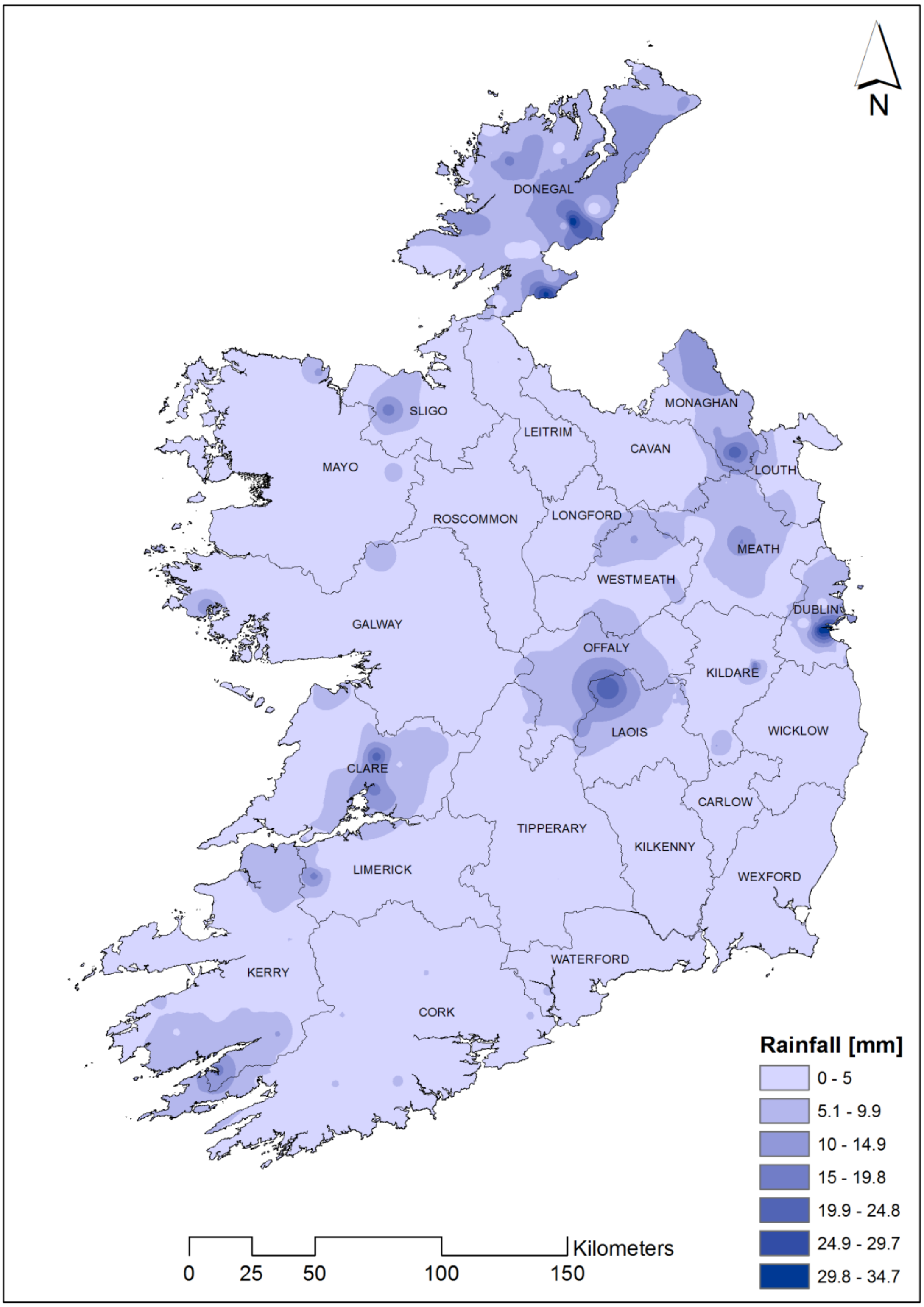

Fig 14. Map showing the distribution of rainfall which lead to localized flash flooding (24-hour rainfall ending 9am July 27th 2013).

4.15 2013/2014, December – February winter storms

TYPE OF EVENT: Windstorm

RETURN PERIOD: N/A

EXTENT: Countrywide

IMPACTS: Widespread flooding, power outages, disruptions to road-traffic and aviation. Severe damages to infrastructure-particularly road and coastal. Over 8,000ha of forest damaged in the storms. 2 resulting fatalities although few other reports of injury.

DAMAGES: €91.9m unadjusted (€91.6m CPI adjusted January 2018), including €59.1m insured unadjusted (€58.9m CPI adjusted January 2018).

FATALITIES: 2

EVENT NARRATIVE: The stormiest winter season in Ireland and Britain in 143 years associated with extreme cyclone clustering. Record-breaking rainfall amounts, wave heights and wind speeds recorded throughout the country. A significant cyclone affecting Ireland and the UK every 2-3 days, of which most severe was storm Darwin producing hurricane-force winds and widespread damage.

KEYWORDS: Windstorm, storm, cyclone clustering, flooding, RWB, NAO.

Introduction

Severe mid-latitude cyclones are the key natural hazard impacting on Ireland, they contribute towards the vast majority of rainfall received and are associated with damaging winds and storm surges (Priestley *et al*. 2017a and 2017b). More damaging than an isolated event however, is a cluster of cyclones characterized by successive low pressure systems moving along the same track within a relatively short period of time. Clustering storms often cause severe and widespread damage due to a cumulative effect and progressively lowered resilience of the environment and society upon which they are impacting (Pinto *et al*. 2014; Priestley *et al*. 2017a).

Several variables contribute to creating a favourable environment for the mid-latitude storm clustering to occur at 55^{o} N. A strong North Atlantic jet stream extending over Ireland for a period of at least one week facilitates the intensification of cyclones as they are crossing the Atlantic and directs them towards Ireland and Britain. Jet stream tends to be more intense and extend zonally towards Ireland, when Rossby Wave Breaking (RWB) occurs both north and south of it, holding it in place and increasing its strength (Pinto *et al.* 2014; Priestley *et al*. 2017). North Atlantic Oscillation (NAO) is also partially responsible for fixing the location of the jet. The more northerly location of the jet is related to the positive phase of the NAO (Priestley *et al.* 2017a).

Winter of 2013/14

The winter of 2013/2014 in Ireland was an extremely wet season with unusually frequent and powerful storms (Met Éireann 2017a). Valentia Observatory, Co. Kerry recorded the wettest February, as well as the wettest winter (DJF), in its 148 years long record (NDFEM 2014). A reanalysis study undertaken by Matthews *et al.* (2014) proved the winter of 2013/14 to be also the stormiest on the 66-year long record, when the frequency and intensity of mid-latitude storms are considered together.

The meteorological conditions in the North Atlantic that lead to the cyclone clustering during the winter 2013/14 included a strong and persistent zonal jet stream extending over Ireland, and held in place by RWB to both its south and its north (Priestley *et al.* 2017a). The mean normalised NAO index values for each winter month indicated a positive phase, and were as follows: December 0.438, January 0.168, February 0.842 (Climate Prediction Center 2017). A positive NAO usually coincides with a more northerly position and intensification of the storm track resulting in wetter, warmer and stormier winters in Western Europe (Ulbrich and Christoph 1999, Visbeck *et al*. 2001).

A combination of frequently recurring storm-force winds coincident with high tides, and accumulated precipitation led to extensive infrastructural damage, widespread flooding and 2 fatalities (NDFEM 2014). Sustained storm-force winds were recorded in Ireland on 12 separate days that season, including hurricane winds and gusts observed during Storm Darwin on February 12th (Met Éireann 2017a).

The overall costs of infrastructure repair and clean-up works estimated for each county by its local authorities (see figure 15), totalled at over €110m and the total insurance claims were estimated by the Insurance Institute of Ireland (pers. comm. June 2018) to be around €156m. Furthermore, these sums are only inclusive of damages sustained in periods December 13th 2013 - January 6th 2014 and January 27th - February 17th 2014 and do not include possible damages from winter storms outside these dates, e.g. storm Xaver of December 5th 2013 which produced storm-force winds and hurricane-force gusts at Malin Head, Co. Donegal (NDFEM 2014, Met Éireann 2017a). Although Xaver caused estimated €763m in damages across Europe (ARTEMIS 2014), Ireland escaped largely unaffected with some power outages, blown down trees and minor flooding in the northwest of the country (Murphy 2013a).

December rainfall

Most of the stations across Ireland reported monthly rainfall values well above their long term averages (LTA), with a number of stations recording their wettest December on record. The highest monthly rainfall relative to the 1981 - 2010 LTA occured at Ballymote, Co. Sligo (251%), where at least 1mm of rain fell on all but one December days. The highest absolute value of 690.3mm was recorded at Cloone Lake, Co. Kerry and amounted to 224% of the station's LTA. 93.6mm of rain fell at Leenane, Co. Galway on December 29th, which was the highest 24-hour value recorded that month in Ireland (Met Éireann 2014a).

January rainfall

Monthly rainfall records for January significantly exceeded the LTA values at almost all stations. Many stations reported twice the average amounts of rain and more than 25% of stations recorded their wettest January on record. The highest percentage of the LTA was recorded in Co. Galway at Drum West station, which received 287.5mm of rainfall amounting to 227% of its 30-year average.

The highest absolute value was recorded at Cloone Lake, Co. Kerry, where 585.4mm of rain accumulated during the month. The highest 24-hour accumulation occured at Kilgarvan, Co. Kerry on January 11th when 68mm of rain fell at the station (Met Éireann 2014b). Notably, at several stations in counties Mayo, Galway, Kerry and Cork at least 1mm of rainfall fell on every day of the month (Met Éireann 2014b).

February rainfall

February was the wettest of the three winter months in 2013/14. The LTA values were exceeded at all stations, oftentimes twice or even three times. Monthly precipitation at Tullaroan in Co. Kilkenny amounted to 344% of the station's LTA. About 1 in every 3 stations recorded its wettest February since the records began. Most notably, the longest standing series of observations at Valentia Observatory, Co. Kerry (148 years) was surpassed with a monthly value of 288.2mm (233% of its

LTA). Multiple stations in Co. Leitrim recorded at least 1mm of rain on all 28 February days (Met Éireann 2014c).

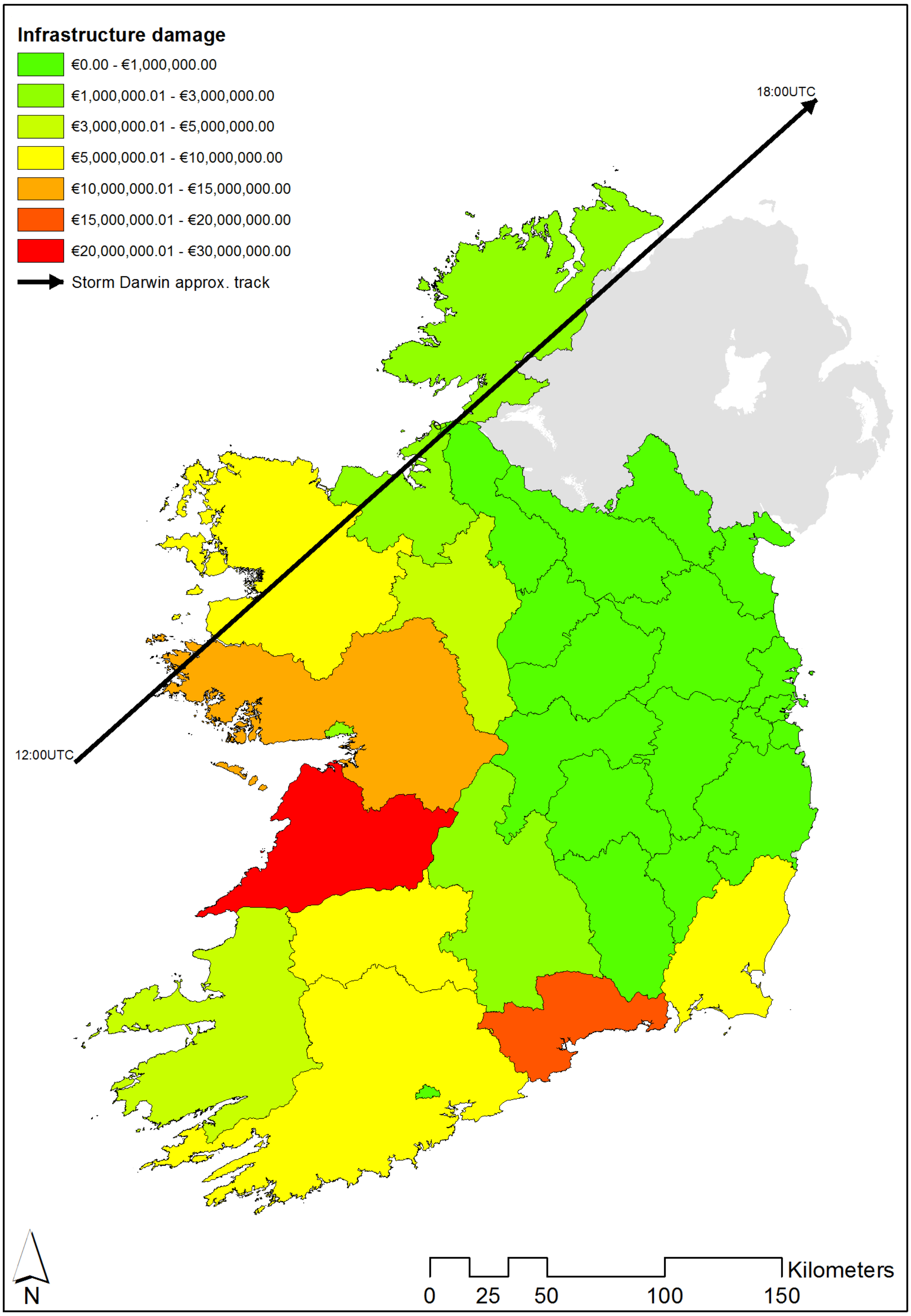

Fig 15. Damages to infrastructure sustained during the stormy winter of 2013/14.

4.16 2014, February 12th Storm Darwin

TYPE OF EVENT: Windstorm

RETURN PERIOD: N/A

EXTENT: Countrywide, strongest in the west and southwest, weakest in the midlands.

IMPACTS: 2 international airports temporarily shut down and aircrafts damaged, 260,000 ESB customers with interrupted power supply, 8,000ha of woodland damaged. Traffic disruptions due to blown down power lines and trees.

DAMAGES: €178.1m unadjusted (€177.2m CPI adjusted January 2018), including €97.6m insured unadjusted (€97.1m CPI adjusted January 2018).
€286m in insured property Europewide.

FATALITIES: 0

EVENT NARRATIVE: Storm originated from an area of low pressure (approx. 1005hPa) south of Nova Scotia on February 10th. Rate of deepening while crossing the Atlantic almost double the 'weather bomb' threshold for the relevant latitude. Northeast track. Landfall in Ireland on the morning of February 12th, hurricane force westerly and south-westerly winds. Weather warnings in effect until the following morning.

KEYWORDS: Windstorm, storm, rainfall.

Meteorological profile

Storm Darwin emerged on February 10th from a low-pressure area to the south of Nova Scotia which deepened as it crossed the Atlantic and was influenced by the cold, northern air masses. The rate at which the storm's minimum central pressure was dropping (record of 39hPa in 24 hours), largely exceeded the 'weather bomb' threshold for the 50ºN latitude (21hPa in 24 hours) defined by Sanders and Gyakum (1980).

The storm approached Ireland from the southwest on the morning of February 12th, it then progressed north-eastwards across the country as the day went on. It attained a minimum central pressure of 955hPa while moving over Ireland and produced gusts of hurricane force [≥33m/s] at 13 separate weather stations, at 3 of which the gusts reached hurricane force 2 [≥43m/s]. In addition, the station located at Shannon Airport recorded its highest ever sustained wind speed of 31m/s and a gust of 44m/s- the highest gust observed in this storm. See figure 16 for highest recorded wind speeds of the storm. 25m high waves were observed off the south coast. The centre of the storm eventually cleared Ireland around 6pm, although the last of the weather warnings remained active until the following morning (McGrath 2015).

Impacts

Remarkably, no fatalities resulting from the storm were reported, despite its strength and inflicted infrastructural damage. Weather warnings were issued for most of the country, including status red warnings for many counties (McGrath 2015). Cork and Shannon airports were temporarily closed during the storm. A parked aircraft was tipped over and several more were hit by airborne debris. Some infrastructural damage occurred at Dublin Airport (NDFEM 2014).

According to the ESB, approximately 260,000 customers had their electricity supply disrupted, many of whom waited several days to have it restored. Fallen power lines, blown down trees and debris blocked many smaller as well as major roads causing widespread traffic and transportation disruptions. (NDFEM 2014). The insurance industry reports put the total amount of claims associated with this storm in Europe at €286m, of which most occurred in Ireland and the UK (ARTEMIS 2015).

In response to the damages to Irish forestry caused by the storm, the Department of Agriculture Minister Tom Hayes T.D. instituted a National Windblow Task Force (NWTF) to carry out a prompt assessment of the location and extent of the damages. The Task Force investigated the aftermath of the storm using remote sensing methods and satellite imagery. The report established that 8,000ha of forests were harmed by the storm, mostly in counties Kerry, Cork, Limerick, Tipperary and Clare, where ¾ of the impacted forests were national forests managed by Coillte and the remaining ¼ were privately owned woodlands. The damage estimates resulting from this assessment are rather conservative as they only considered gaps in the forest canopy larger than 0.5ha in area, and also disregarded partially blown trees i.e. still standing at a 45^0 angle (McInerney *et al.* 2016).

Munich RE reinsurance company (pers. comm. May 2018) estimated the overall damages caused by this storm to be in the region of €170m, including €97.6m in insured losses.

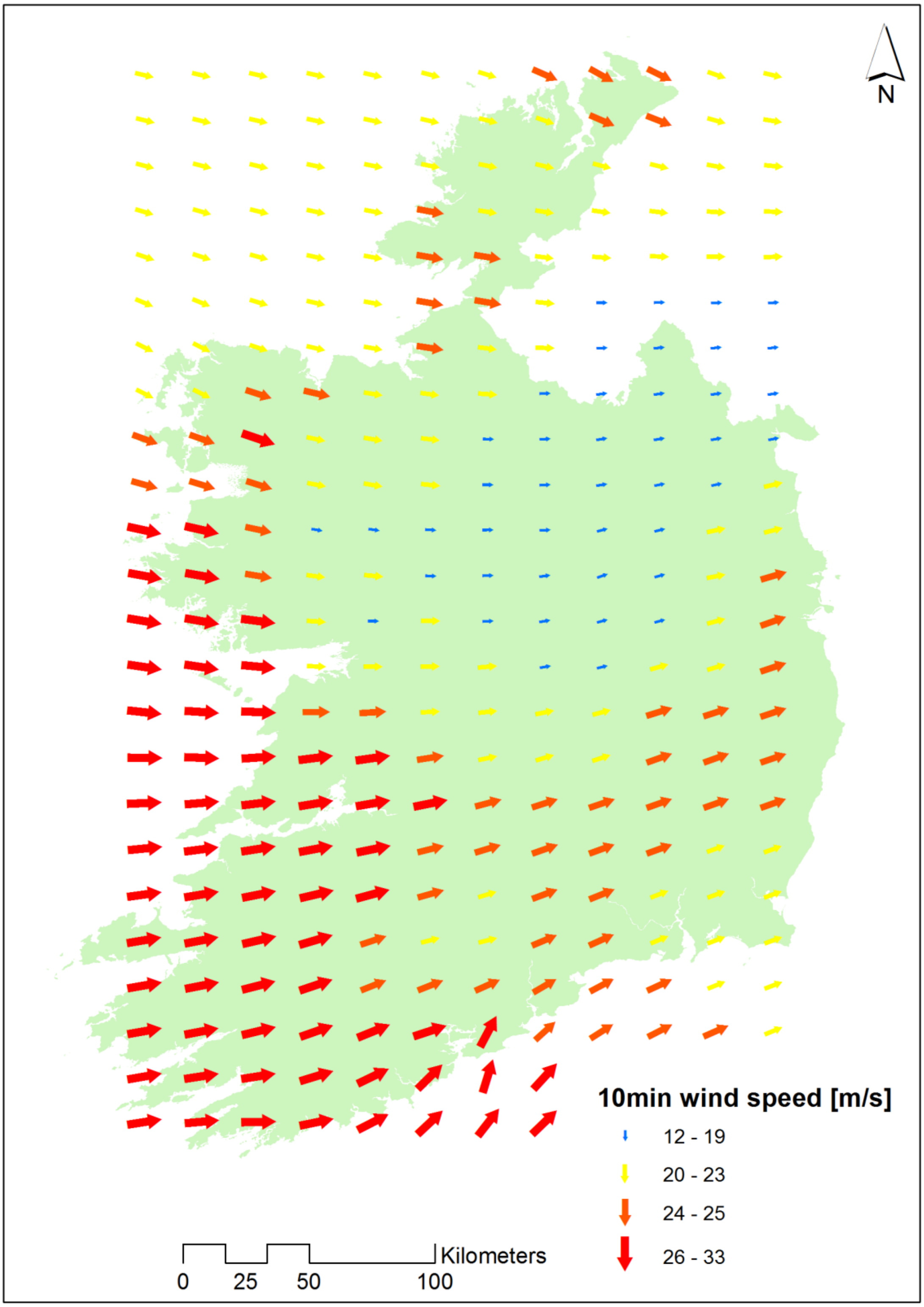

Fig 16. Maximum 10-minute wind speeds and their directions recorded during storm Darwin at 22 weather stations across Ireland and interpolated for the whole country. The west and southwest of Ireland stand out as the most affected by the storm.

4.17 2015/2016, December – February extremely wet winter

TYPE OF EVENT:	Rainfall/ flooding/ windstorm
RETURN PERIOD:	N/A
EXTENT:	Countrywide
IMPACTS:	Widespread flooding throughout the country. 3 distinct flooding events occurred in the aftermath of storms Abigail (November 12th, northwest), Desmond (December 4/5th, west of the Shannon) and Frank (December 29/30th, south, southeast and east of Shannon). Over 1100 houses and businesses flooded, 600 dwellings evacuated, many more cut off. Thousands of hectares of farmland inundated. 350,000 ESB customers without power in December alone.
DAMAGES:	€199.6m unadjusted (€199.8m CPI adjusted January 2018), including €70m insured unadjusted (€70.3m CPI adjusted January 2018).
FATALITIES:	1
EVENT NARRATIVE:	Wettest winter on record with 189% of usual rainfall. Most seasonal mean temperatures around 1°C above LTA. Heavy rainfall events originating from mid-latitude storms of which 6 impacted during December, January and February. Ground conditions already saturated leading up to the season thanks to a wet and stormy November. 248% of normal winter rainfall recorded at Roche's Point, Co. Cork; highest 24-hour total occurred at Keenagh Beg, Co. Mayo with 165mm of rain.
KEYWORDS:	Windstorm, storm, flooding, extreme rainfall.

Meteorological profile

The winter of 2015/16 was warmer, stormier and, especially, wetter than on average. Many precipitation as well as temperature records were broken across Ireland. The seasonal average rainfall in Ireland amounted to 602mm (189% of the LTA), making it the wettest winter since records began (NDFEM 2016). Most weather observing stations recorded mean seasonal temperatures between 0.5^{o}C and 1.1^{o}C higher than their respective long term averages (LTA; Met Éireann 2016a).

Although the meteorological winter is limited to December, January and February, this analysis will discuss certain features of November 2015 as its wet and stormy conditions exacerbated the impacts of the weather in the months that followed (NDFEM 2016).

Contrary to tropical cyclones and hurricanes, mid-latitude storms are not typically given names, unless they are very significant (McGrath 2015). Six notable and named storms impacted upon Ireland during the 2015/16 winter- Desmond (Dec 4/5th), Eva (Dec 23rd), Frank (Dec 29th/30th), Gertrude (Jan 29th), Henry (Feb 1st) and Imogen (Feb 7/8th). The strongest sustained wind speed of the season was recorded during storm Frank (28m/s), while the strongest gusts were produced by storms Eva and Imogen (38m/s; Met Éireann 2016a). Three more storms occurred during November 2015, of which the most notable, due to resulting flooding, was Abigail which occurred on November 12th. Overall the 2015/16 winter (DJF) experienced 10 days with storm force winds and was the fifth stormiest winter of the preceding decade (NDFEM 2016).

The winter of 2015/16 was also extremely wet, largely due to precipitation associated with passing Atlantic depressions (Met Éireann 2016b). Seasonal, as well as all monthly rainfall totals were above the long term average at every weather station in Ireland; more than half of the stations experienced their wettest winter on record (Met Éireann 2016a). Winter accumulations varied from 134% of the LTA at Mace Head, Co. Galway to 248% of the LTA at Roche's Point, Co. Cork, while December totals reached 300% of the LTA in the south, where Cork Airport recorded more precipitation in December than it usually does in the entire winter season

(NDFEM 2016). The highest seasonal total of 823.4mm was recorded at Valentia Observatory, Co. Kerry (Met Éireann 2016a). The highest daily accumulation occurred at Keenagh Beg, Co. Mayo where a staggering 165mm was recorded in just 24 hours (NDFEM 2016). Stations at Cloyne, Co. Cork and Leenane, Co. Galway recorded the second and third highest daily amounts with 90.9mm and 90.3mm respectively (Met Éireann 2016c).

Impacts

Persisting rainfall and its accumulation combined with soils already saturated after a wet November, resulted in the worst flooding ever experienced in Ireland. Most severe flooding occurred in the aftermath of the mid-latitude storms which brought immense precipitation. Three of those storms produced widespread flooding and record flood peaks across Ireland, they were Abigail (November 12th), Desmond (December 4/5th) and Frank (December 29/30th). 72 out of 75 analysed OPW operated water level gauges, recorded their highest (37), second highest (23) or third highest (12) flood peak levels. This reference network of gauges proved the winter floods of 2015/16 to be more significant than those of November 2009, and hence making them the most severe floods on record (NDFEM 2016).

Floods which ensued from storms Desmond and Frank were the most widespread and damaging. In the case of storm Desmond the flooding occurred mostly west of the Shannon river and lasted from December 6th to December 13th. Storm Frank in turn affected mostly the south and southeast of the country and the eastern bank of the Shannon, and occurred between December 29th and January 5th. This event broke records for the highest water levels at five different stations on river Shannon (NDFEM 2016).

Some places, like Bandon, Co. Cork, experienced recurring flooding this winter, and even though the water levels were higher in many locations, the overall number of flooded properties was less than during the November 2009 flooding (NDFEM 2016).

Overall, 543 houses and 606 businesses were flooded and many more were threatened by rising water levels. 601 residential dwellings were evacuated, while 2393 more were cut-off by the floodwaters. Thousands of hectares of agricultural land were inundated, farm activity limited and animal welfare concerns raised. Multiple government assistance schemes were activated to supplement the purchase of emergency feed and repair damaged farm infrastructure (NDFEM 2016).

Flights and ferry services were disrupted and temporarily suspended, due to the violent winds associated with passing storms. The flooding itself impacted mostly on road and railway networks and €110m were made available by the government for the repair works. Pavement disintegration, road subsistence, coastal erosion and bridge scouring all contributed to the closure of many major and minor roads as well as sections of the railway network. Traffic, bus and train service disruption ensued (NDFEM 2016).

December was by far the month of largest power outages to ESB customers, with 4,000 line faults responsible for a total of 350,000 customers without electricity. However, except for the storm Frank on December 29/30th when over 80,000 customers lost supply, most disruptions were localized and short-lived (NDFEM 2016).

23,000 Irish Water customers were put on 'boiling notices' due to contamination on fresh water supply, many of these notices were still in effect months after the event (NDFEM 2016).

The Insurance Institute of Ireland (pers. comm. June 2018) estimated the overall insured damages to be €70m. Insured damages combined with damages to infrastructure and government payments made under various assistance schemes listed in the NDFEM report (2016), add up to a staggering €199.6m.

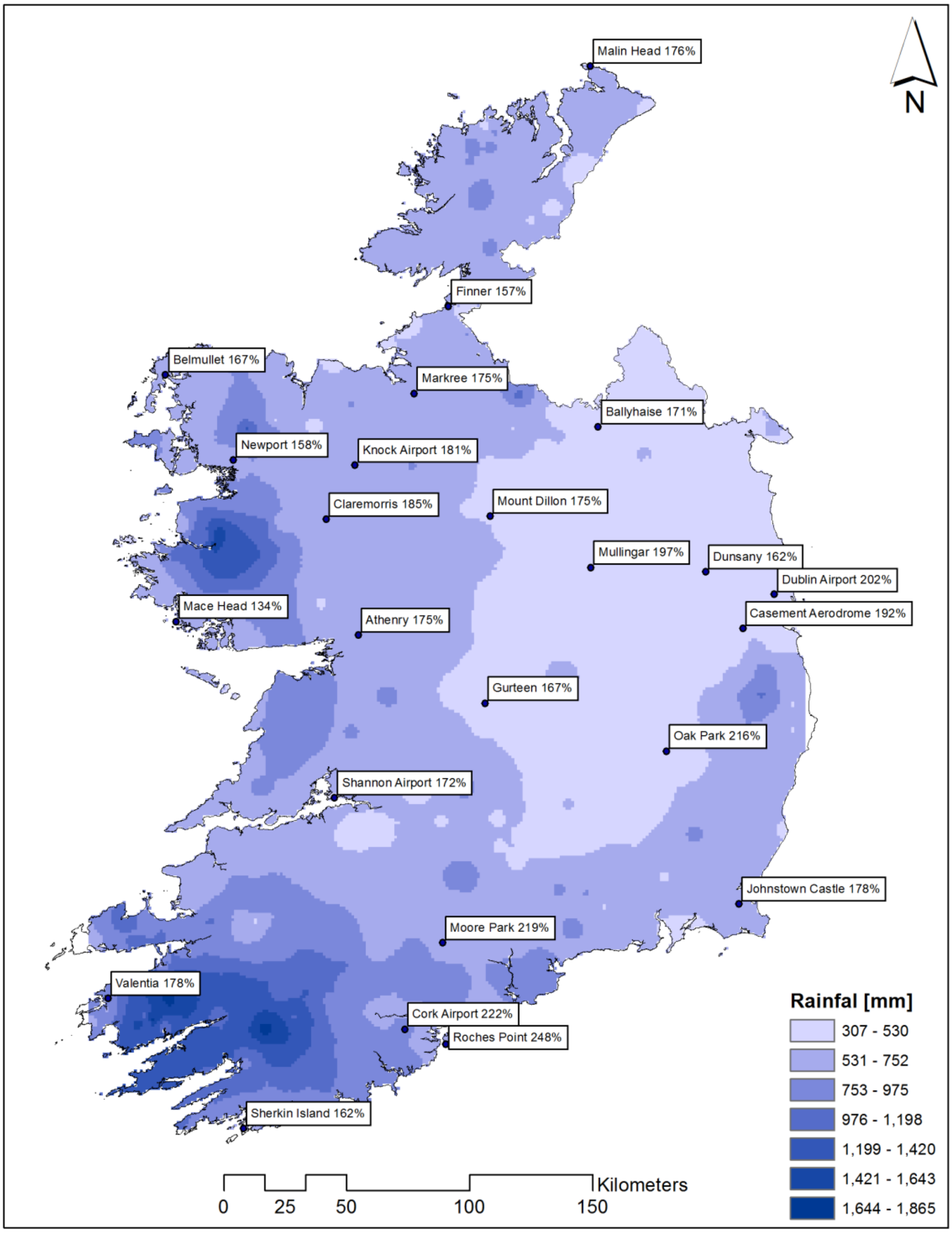

Fig 17. Visibly more rain fell in the western part of Ireland, with the counties Mayo, Galway, Kerry and western part of Co. Cork bearing the worst of it. Marked on the map are 24 principal weather observing stations and the received percentages of their respective average winter rainfall.

4.18 2017, August 22nd northwest flooding

TYPE OF EVENT:	Extreme rainfall/ flash flood/ landslide
RETURN PERIOD:	N/A
EXTENT:	Regional; Counties Donegal, Tyrone and Derry
IMPACTS:	Inishowen Peninsula, Co. Donegal worst affected. Burst mains and shortages in freshwater supply; 25,000 dwellings temporarily without power. Tens of people register as *misplaced* and some 100 people having to be rescued by emergency services. Some loss of livestock animals. Collapsed bridges, parts of roads washed away, overall 1500km of road network damaged. Widespread damage to infrastructure and property.
DAMAGES:	€42.1m unadjusted (€41.4m CPI adjusted January 2018), including €27.1m insured unadjusted (€26.6m CPI adjusted January 2018).
FATALITIES:	0
EVENT NARRATIVE:	Remnants of post-tropical storm Gert wrapped up in a low pressure system travelling east across the North Atlantic make landfall in Ireland on August 22nd 2017. Northwest of Ireland experiences extremely intense but very localized rainfall; no significant winds recorded. Widespread flooding and 2 instances of landslide occur as a result.
KEYWORDS:	Flood, flash flood, flooding, landslide, extreme rainfall.

Meteorological situation

August 2017 in Ireland was rather cold and dull, yet for the most part well within its normal scope of variability. All twenty-five principal weather stations recorded mean temperatures somewhat below their 1981 - 2010 long term average (LTA) and the number of recorded sunshine hours was also below the LTA at most stations. Overall, August was unexceptional in terms of precipitation with monthly totals ranging from 75% to 185% of the LTA across the country, and only one day with gale force winds was recorded (Met Éireann 2017b).

However, one event of localised extreme rainfall took place in the north western part of the country, causing extensive and severe flooding and landslides (Donegal Now 2017, Maguire 2017a).

In the early morning of the 13th of August the United States National Hurricane Center (NHC) issued its first public advisory notice on the tropical depression no. 8. The NHC continued to issue updates on the storm four times daily until the evening of the 17th of August, when the storm moved away and no longer endangered the East Coast of the United States (NHC 2017a).

The initial tropical depression developed east of the Bahamas and began to travel north-northwest towards the United States. It had an estimated minimum central pressure of 1011hPa and sustained winds of up to 16m/s. With the decreasing pressure and strengthening winds, the depression evolved into a tropical storm, and received the name Gert on the evening of August 13th (NHC 2017a). Gert attained hurricane force in the early morning hours of August 15th, and began to veer northeast. Now travelling away from the continent, Gert continued to increase in strength and attained its maximum strength around 3am on August 17th, reaching 47m/s in sustained winds with stronger gusts and a minimum central pressure of 967hPa. From there on, the hurricane began to weaken quickly as it continued to move northeast into the colder waters of the North Atlantic, and was reduced to a post-tropical storm by the evening of August 17th (NHC 2017a).

The remnants of Gert became absorbed by another low pressure system travelling across the Atlantic, before making landfall in the northwest of Ireland in the afternoon of the 22nd of August. The low pressure weather system brought extremely heavy, although very localised, rainfall yet no significant winds. North Co. Donegal was most affected with an extremely high 77.2mm of rain being recorded at Malin Head weather station, most of which fell in the space of just 8 hours (Fleming, 2017). 24-hour rainfall distribution (ending 9am August 23rd) is shown in figure 18. This was the second wettest day (and the wettest August day) recorded at Malin Head since 1955. The only wetter day recorded was December 5th 2015 with 80.6mm of rain. However, on that day the precipitation was more evenly spread over a 24-hour period. At Malin Head, August 2017 as a whole received 185% of the LTA rainfall, where the abovementioned event was responsible for 83% of this total.

Impacts

This downpour resulted in flash flooding in the eastern part of Co. Donegal, Co. Tyrone and Co. Derry/Londonderry. Flood waters caused severe structural damage to major roads and destroyed bridges (McClements 2017, McClements *et al*. 2017). Many homes and businesses were damaged and local farmers reported losing farm animals to the flood waters (Highland Radio 2017a). Tens of families registered as misplaced and worked with the local council to avail of temporary accommodation due to their homes being inundated (Maguire 2017b). The city of Derry was virtually inaccessible by road and its airport had to temporarily shut down and cancel all flights (Highland Radio 2017b).

Worst affected however was the Inishowen Peninsula in Co. Donegal, where the damages included collapsed bridges and some roads being simply washed away. Some 1,500km of the road network were affected by the disaster on the Peninsula alone, parts of which are expected to remain impassable for weeks (Maguire 2017b).

There were power shortages following the rain, caused by the flooding as well as lightning strikes. The Electricity Supply Board (ESB) estimated that at the height of the storm some 25,000 dwellings were without power throughout the country. On

Inishowen 1,600 homes were still without power the following afternoon. In many cases it was deemed unsafe to restore the power until the flood waters have receded (McNeice 2017). Irish Water has announced several burst mains and damages to wastewater infrastructure due to flooding, causing shortages in freshwater supply on the Peninsula (McNeice 2017). At least two instances of landslides were also reported occurring at Grainne's Gap, near Muff, and a smaller one in Urris (Donegal Now 2017, Maguire 2017a).

With more than 100 people having to be rescued by the emergency services from their stranded cars or flooded properties, it is surprising that no serious injuries or deaths resulting from this event were recorded (McClements *et al*. 2017).

Munich RE (personal communication, May 2018) estimated the overall damages caused in this event to be in the order of €42m.

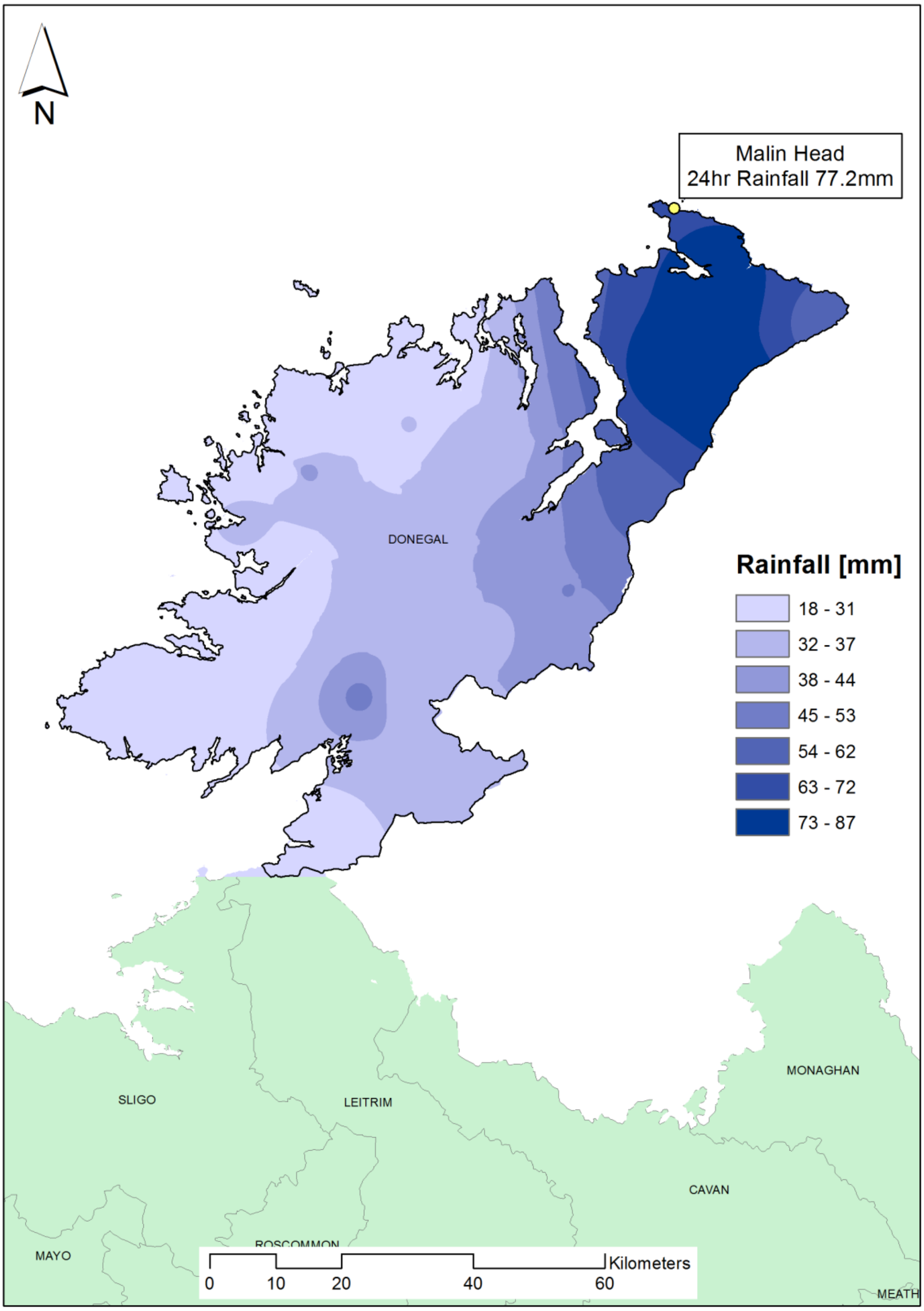

Fig 18. Distribution of extreme rainfall which led up to severe flooding in Co. Donegal (24-hours ending 9am August 23rd).

4.19 2017, October 16th Storm Ophelia

TYPE OF EVENT:	Extra-tropical Storm
RETURN PERIOD:	N/A
EXTENT:	Countrywide with South and West worst affected
IMPACTS:	Hundreds of trees and electricity poles blown down causing major road blockages and power outages to approx. 385,000 dwellings and premises. 3 separate fatal accidents all directly caused by the weather. Schools and Universities closed. Court hearings, medical procedures, postal and public transport services cancelled. Over 200 flights cancelled. Severe damage to buildings and many instances of flooding.
DAMAGES:	€71m unadjusted (€70.3m CPI adjusted January 2018), including €45m insured unadjusted (€44.6m CPI adjusted January 2018).
FATALITIES:	3
EVENT NARRATIVE:	The most eastern hurricane ever recorded, originating to the southwest of the Azores. Intensifying into a tropical storm and later into a category 3 hurricane named Ophelia it travelled northeast towards Ireland. Despite SSTs below 27°C it strengthened due to cooler air in the upper-level and low wind-sheer. Undergone extratropical transition before making landfall but propelled by the jet stream it retained most of its strength. Moderate rainfall in the west but violent storm-force winds were the main feature of this event.
KEYWORDS:	Storm, extra-tropical, hurricane, Ophelia, flood, flooding.

Meteorological situation

Hurricane Ophelia first began as an upper-level trough southwest of the Azores archipelago on October 1st 2017. It hovered around and intensified for over a week before it was classified as a tropical depression by the National Hurricane Center (NHC) on October 9th at 9am. From thereon the NHC tracked the storm's development and issued advisory notices every 3 hours (Met Éireann 2018c, NHC 2017b). In the morning of October 10th Ophelia began moving southeast and quickly intensifying. By early Wednesday morning, October 11th, Ophelia was recognized as tropical storm and became a hurricane later the same day, it also assumed a north-easterly direction. Despite the somewhat insufficient SSTs (approx. 26.5^{o}C), Ophelia continued to strengthen as it moved northeast thanks to cooler air in the upper-level and low wind-shear. Thanks to those conditions sustaining convection, on Saturday, October 14th, it attained a category 2 and subsequently category 3 status. Although the hurricane weakened during Sunday, October 15th and had eventually undergone the extratropical transition, it got caught in a fast-flowing trough trailing just behind an upper-level jet-streak. Thanks to those conditions, although no longer a hurricane upon landfall, Ophelia maintained its strength close to hurricane-force and deepened its minimum central pressure to 959.3hPa at 11am on October 16th as it passed over Valentia Observatory, Co. Kerry (Met Éireann 2018c, Hermida 2017, NHC 2017b).

The rainfalls associated with Ophelia were in order of 17mm (Valentia Observatory, Co. Kerry; Mace Head, Co. Galway), but the most damaging feature of this storm were its winds. The highest sustained wind speed was recorded at Roches Point, Co. Cork at 32m/s (equivalent to Beaufort 11 *violent storm* and only 0.7m/s short of Beaufort 12 *hurricane-force*), while the strongest gust was 43m/s, also recorded at Roches Point (Met Éireann 2018c, Hermida 2017). Highest wind speeds recorded during this event are shown in figure 19. Record breaking waves at several buoys and the Kinsale Energy Gas Platform which recorded its highest wave on its 24-year record at 26.1m (Met Éireann 2018c).

Advisory notices were issued by Met Éireann on Thursday, October 12th and Friday, October 13th, though there was still a large degree of uncertainty about the possible track and strength of the storm. On Saturday, October 14th, Met Éireann has issued a Red Wind Warning for counties Cork, Kerry, Clare, Galway and Mayo, which was extended to the rest of the country by the next day's evening. The warnings also informed of the expected storm-force winds, hazardous marine conditions, potential flooding, possible damages to structures and risk to lives (Met Éireann 2018c).

Ophelia was the 10th and last hurricane of the particularly intense and damaging 2017 season. It also set the record as the farthest east occurring major (category 3 or higher) hurricane (Hermida 2017, Met Éireann 2018c).

Impacts

Ophelia made landfall in Co. Kerry at around 11am on Monday, October 16th and trailed towards Co. Donegal, wreaking havoc on its way across the country. As vegetation was in full leaf it was more vulnerable to high winds due to its larger surface area. Hundreds of trees and electricity poles were blown down causing some 300,000 households and 85,000 business premises to be left without electricity. Water treatment and supply also disrupted. Schools and Universities closed, court hearings and hospital medical procedures cancelled. Transport widely disrupted with road closures and flight cancellations, bus, rail, ferry and postal services not operational (Met Éireann 2018c, Hermida 2017).

More than 500 trees blown down in Cork City alone, severe structural damage to Turner's Cross stadium and a roof blown off a sports hall of one of the schools in Douglas. In Kerry hundred mature trees down, many roads blocked and flooding in multiple locations. Coastal defences breached by the storm surge in Salthill, Galway City, resulting in severe flooding. Limerick has also experienced high winds and localized flooding. Dublin affected but not to the same extent as the south and west, Dublin Fire Brigade cleared over 70 blown down trees. Tragically, three lives were lost as a direct result of the severe weather (Met Éireann 2018c).

The Insurance Institute of Ireland (pers. comm. June 2018) estimated this event to cause €45m in insured damages in Ireland, while Munich RE (pers. comm. May 2018) calculated the overall cost of Ophelia in Ireland to be €71m. Other reports have estimated the overall losses to be much higher, especially when including losses from reduced economic output; these estimates varied from between €500m and €800m (Gallin 2017) to U$1.8b- somewhat of an outlier among the estimates (Flanagan 2017).

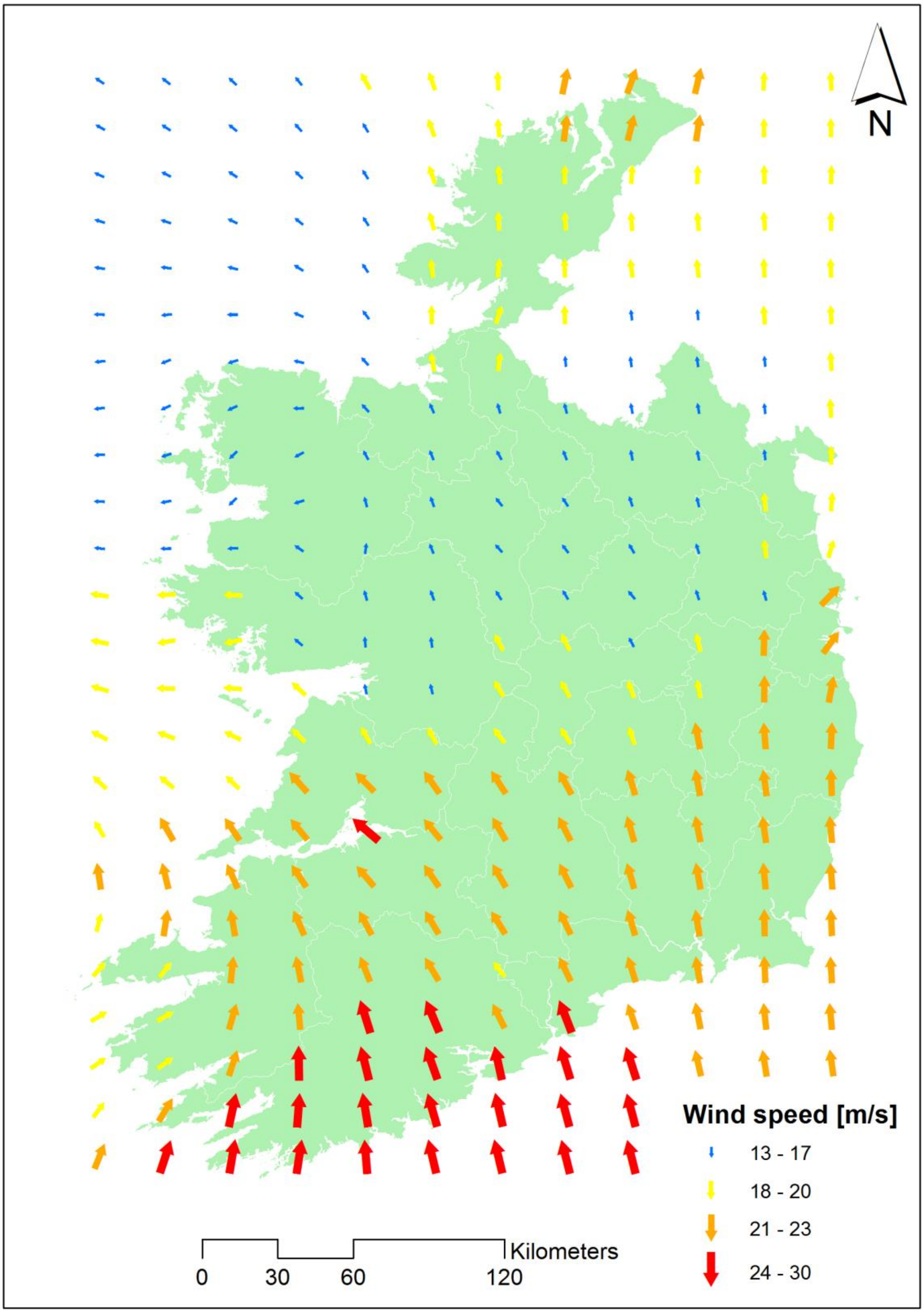

Fig 19. Maximum 10-minute sustained wind speeds and directions during storm Ophelia.

5. Results

5.1 Introduction

This chapter sets out to present and analyse trends in the gathered data. Firstly, the frequency of occurrence of weather extremes is discussed as more extreme events simply equals more losses. This is followed by the analysis of the economic cost of weather extremes, changes in per capita GDP, population change and distribution. Finally, trends are compared and the relationship between societal change, economic growth and the cost of high-impact events is discussed. Only straight-forward statistical methods (linear regression model and polynomial function) are applied to the data, yet given the presently small sample size (19 events) the results are not exempt from bias. To produce more robust results a larger sample size is needed which can be achieved by either temporally expanding the inventory or including less impactful weather events.

5.2 Identified extreme weather events

Nineteen events were found to meet the thresholds and criteria described in chapter 3 during the period 2000 - 2017. Arranged chronologically, they are presented in figure 20.

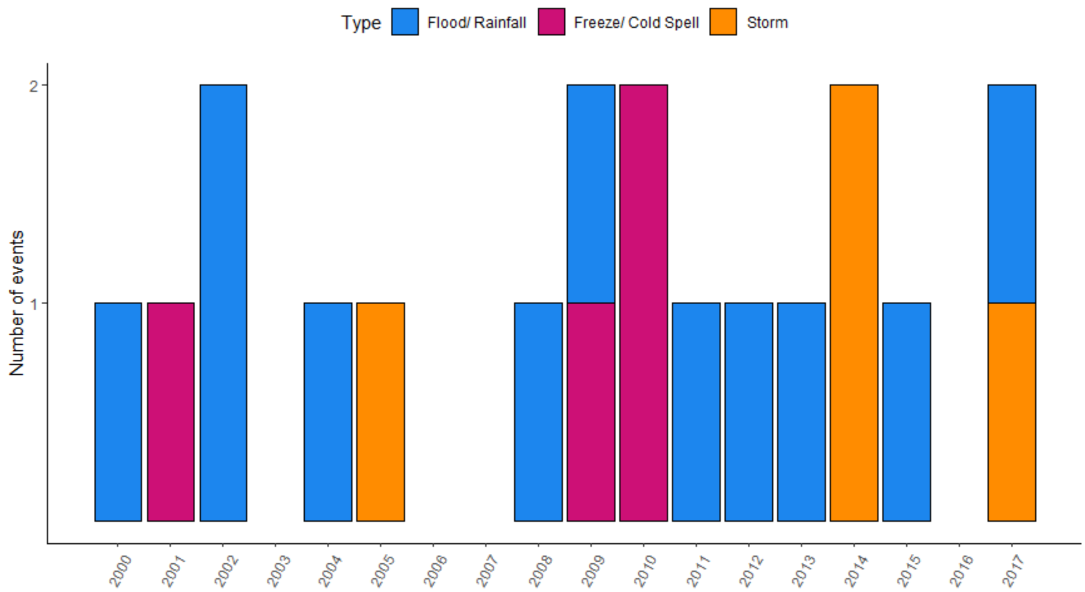

Figure 20. Number of extreme weather events in Ireland between 2000 and 2017 by type.

Eleven flooding/extreme rainfall events were identified, making it the most common type of event in this study (58% of total), while storms and cold spells were equally common with 4 events of each type (21%). There were four years with no extreme weather events meeting the criteria of this study and five years with two events, the remaining nine years recorded a single event each. Seven events happened during the first half of the study period while 12 happened in the second half, showing a significant increase in the frequency of occurrence as shown by the linear regression model fitted in Figure 21, although at least part of this increase could be attributed to interannual variability given the relatively short timespan of the study. Nonetheless, despite the multimodal distribution of the data, both the linear regression and the polynomial function indicate an increase in frequency over time.

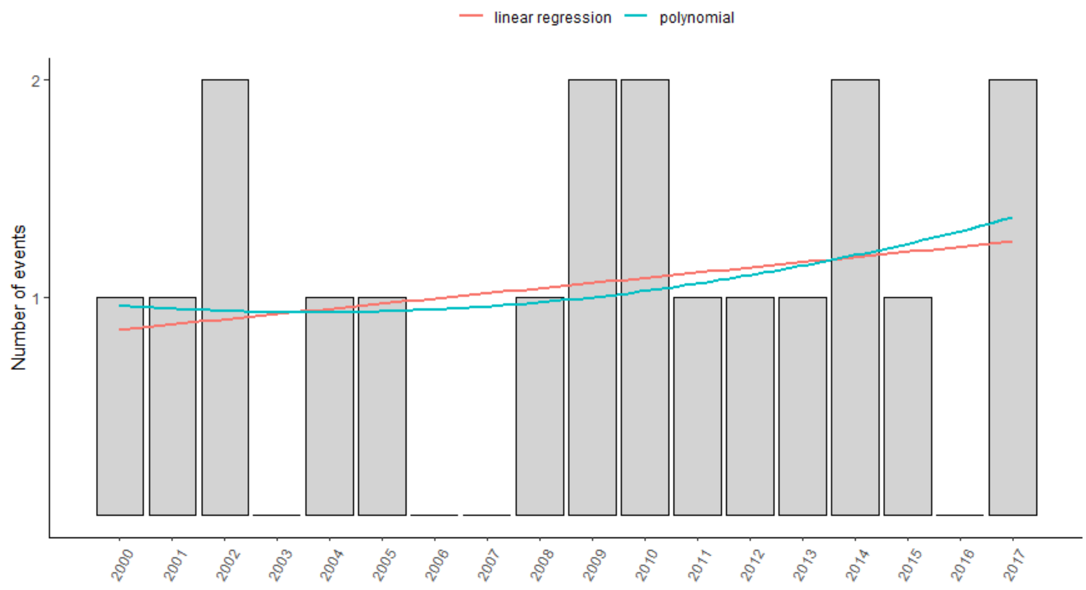

Fig 21. Frequency of extreme weather events in Ireland fitted with linear regression model and a polynomial function both indicating a positive trend.

One more event was found to meet the financial threshold, namely the fodder crisis of 2012/2013. However, it was not presented in chapter 4 and will not be included in further analysis. The reason for exclusion of this event is that it was not caused by a single meteorological event but was rather a consequence of a sequence of irregular seasons. It was an especially complex event without an easily defined cause, moreover, fodder stock management was an important factor in this event and exacerbated its magnitude. Nonetheless a consequence of extreme weather with extremely high economic losses, an analysis of the 2012/2013 fodder crisis is included in the appendices (appendix A).

5.3 Losses

Extreme weather events in Ireland generated over €2.7bn in economic losses in the 2000 - 2017 period. This figure is a product of the applied financial threshold for the inclusion of events in this study and would likely be significantly higher if less damaging events were also selected. For example, the Munich Re's NatCatSERVICE dataset indicates US$ 3.4bn (approximately €3bn) in losses for the same period (NatCatSERVICE 2019). While this study's figure of €2.7bn resulted from 19 events, Munich RE's €3bn came from a total of 66 analysed events. This relatively small difference (~11%) shows that vast majority of losses come from a small number of disastrous events.

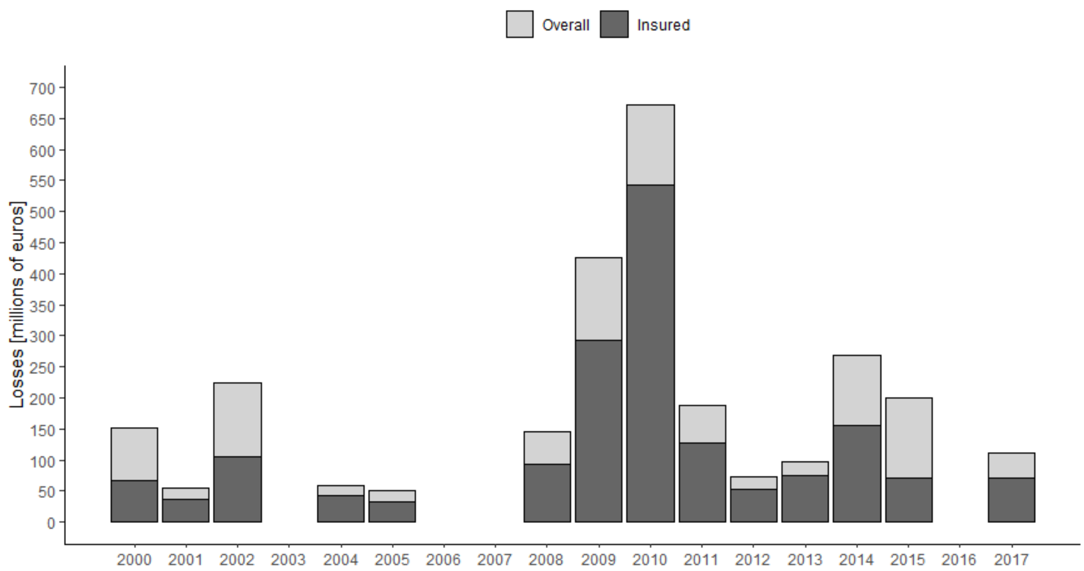

Figure 22. 2000 - 2017 annual economic losses from extreme weather in Ireland and their insured components.

A spike in the loss data occurred in 2009 and 2010 when 4 especially devastating events happened in two consecutive years, jointly amounting to €1.1bn (40% of total). These events were a single devastating flood and winter damages of 3 consecutive, extremely cold winters. Otherwise, there appears to be a large degree of interannual variability, nonetheless three years free of weather extremes in the first half of the time series and consistently higher losses in the second indicate an overall increase over time represented by the linear regression model (figure 23).

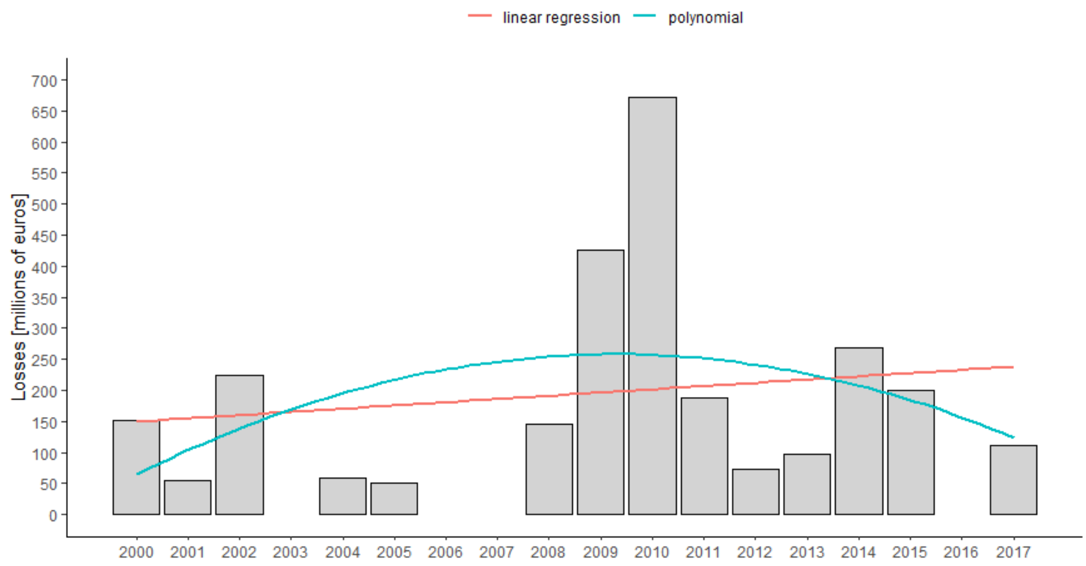

Figure 23. Overall losses 2000 - 2017 adjusted for inflation to January 2018 values. Despite a significant spike in the middle of the time series and a multimodal distribution of data, the fitted linear regression model shows a positive trend.

5.4 Return periods

Return periods available from secondary sources are included in extreme events' profiles, these however were only found for 8 out of 19 analysed events. Moreover, estimation methods and datasets used were often not disclosed, making it difficult to compare individual events or analyse overall trends. Nonetheless, where available, the encountered return periods were mostly in excess of 100 years and even up to and beyond 500 years. This shows that although the applied threshold for inclusion of events in this study was financial, the severity of selected events is also reflected in their return periods. Also clustering of extreme weather events with return periods of 100 years or more, may indicate that they are becoming more frequent under the shifting climatic conditions. This is well illustrated by two flooding events which occurred in Dublin in February (chapter 4.3) and November (chapter 4.4) of 2002. Despite differences in the nature of those floods (fluvial vs coastal) they both had estimated return periods of over 100 years and occurred within 10 months of each other at the same location.

Return periods are calculated individually for events of particular type, magnitude and duration as well as for particular locations. Their values are not static and depend on the referenced dataset. De Gaetano (2009) demonstrates this relativeness by recalculating return periods for extreme precipitation events in the United States. Extending the reference dataset from 1950 – 1979 to 1950 – 2007 resulted in a decrease of return intervals of approx. 20% at most locations. Moreover, referencing those same events to the 1978 – 2007 dataset produced a 30 – 40% decrease in return period values depending on the locality within the United States. This means that the analysed precipitation extremes became somewhat more common after 1978 and hence their return intervals decreased (De Gaetano 2009).

Return periods of extreme precipitation events will also likely be affected by the warming climate. In a case study from Uttarakhand, northern India, Kumari *et al.* (2019) investigated the extreme rainfall event which lead to the disastrous flood of June of 2013. Research revealed that precipitation events of similar magnitude and with an estimated return period of over 100 years would be reduced to a 1-in-39 years event under 1.5^{o}C of global temperature rise, and to a 1-in-23 years events in a 2^{o}C warmer world (Kumari *et al.* 2019).

Return period values, often also expressed as the annual exceedance probability (AEP), are commonly used to quantify and communicate risk. Flood Risk Management Plans published by the Office of Public Works in Ireland in 2018 (FloodInfo.ie 2019) include 40,000 maps which assess the risk of flooding of vulnerable areas and communities under several flooding scenarios, i.e. during a 10-, 100-, and 1000-year flood. Given the importance of changing climate and its influence on the extreme precipitation events, Cooley (2013) argues that such estimates are typically calculated under a stationary climate and stresses the importance of accounting for non-stationarity in risk assessment.

5.5 Fatalities

An analysis of the number of deaths resulting from extreme weather events produces a positive trend over time (figure 24). Of the 15 fatalities recorded from the events included in this study, all but two occurred in the second half of the analysed time period. Deaths were evenly spread across the type of events with floods, storms and cold spells each producing five fatalities. However, since there were 11 flood events, the ratio of fatalities per event was 0.45, meanwhile there were only 4 storms and 4 cold spells and hence their ratio was higher at 1.25 deaths per event.

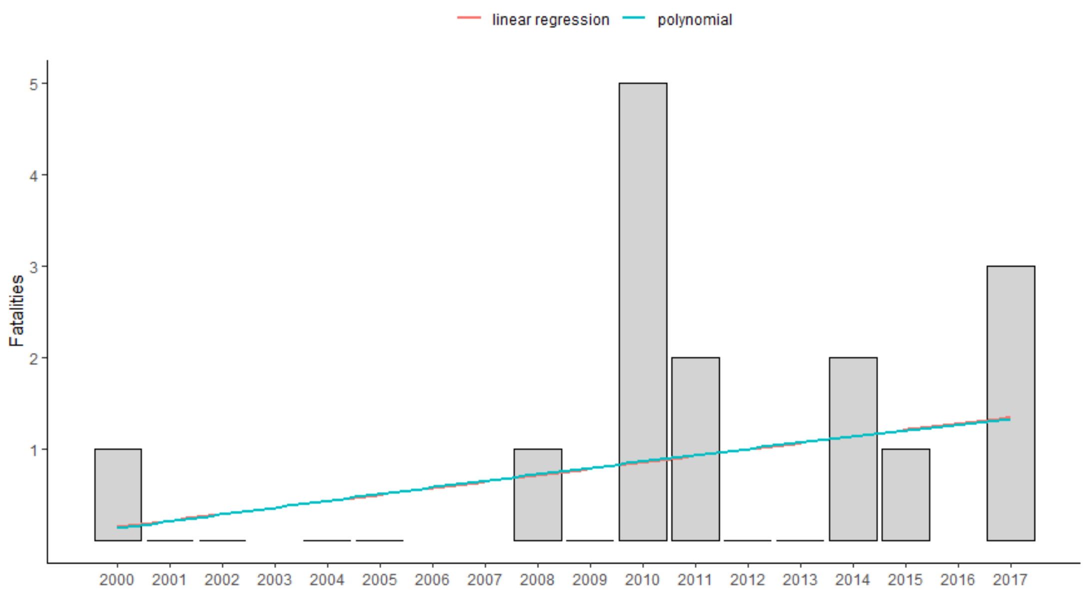

Fig 24. Number of fatalities resulting from extreme weather events in Ireland 2000 – 2017. Linear regression and polynomial function unanimously show a positive trend over time.

Trends differ between regions, but heatwaves appear to increase the number of lives they claim globally, although this can, at least partially, be attributed to advancing urbanization and demographics of age and poverty (Changnon *et al.* 2000, Bouwer 2011, Mahapatra *et al.* 2018). Ireland has not experienced any significant heatwave events during the study period.

Small total number of events and a short study period have limited potential for drawing definite conclusions. Adaptation measures such as improved building design and infrastructure, more accurate forecasting and early warning systems are also likely to have an impact on the number of fatalities and should be considered as factors.

5.6 Population rise and demographic shift

2000-2017 World Bank data (2019a) on population was compiled to find an overall increase in the population of Ireland of 26.4%, which accounts for just over 1 million persons (figure 25). During this period, the population rise rate in Ireland was higher than the global average which was 22.8%. Figure 25 also shows the annual population change rates, where the impact of 2008 economic recession is clearly visible. While during the years of economic prosperity between 2001 and 2007 the population was rising at an ever-increasing rate and actually almost doubled from 1.6% to 2.9%, it rapidly fell as the economy crashed in 2008 to 2%, then to 1% in 2009 and 0.5% in 2010. Despite the crisis, population in Ireland kept rising, although at a slower rate. The rate was stable at around 0.5% between 2010 and 2013, before starting to steadily rise again from 2014 onwards.

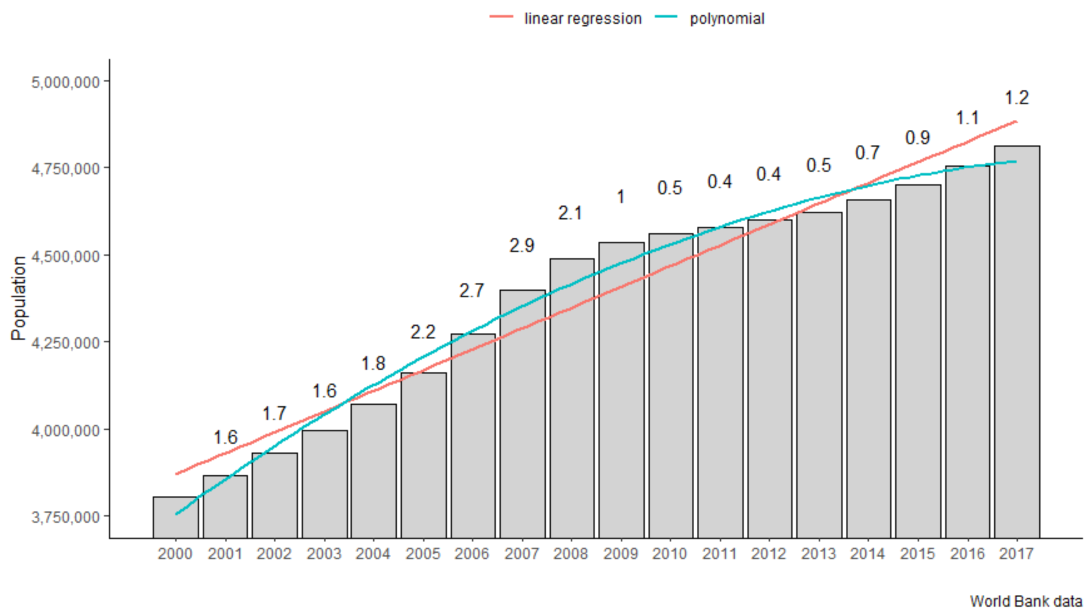

Figure 25. Population rise in Ireland with a fitted linear regression model and a polynomial function. Between 2000 and 2017 the population of Ireland has increased 26.4%, an equivalent of over 1 million people. Numbers above each column represent percentage of increase from previous year.

Certain spatial trends can be discerned in figure 26, which illustrates population change in Ireland, per Electoral Division (ED), between 2002 and 2016 censuses. A concentration of areas where population has decreased is apparent along the Atlantic fringe, with especially large clusters in northwest Mayo, Connemmara and the Iveragh Peninsula, Co. Kerry. Further population decreases occurred also along the east Kerry border, in southeast Galway, west Clare, and on the Cavan-Leitrim border. These are all rural areas in the western half of Ireland.

Meanwhile the eastern half of the country appears to have largely increased the number of its residents, with particularly high increases clustering around Drogheda and southeast Meath, eastern Wexford and throughout Kildare. Figure 27 provides a closer look at Co. Dublin, where an apparent demographic shift towards suburbia took place. Most of the decreases happened in the city itself and the inner parts of South Dublin and Dún Laoghaire/ Rathdown councils, while their outer fringes experience population rise. Population change in Fingal was remarkable with very large increases throughout and several areas (Dublin Airport, Dubber and The Ward) experiencing from six to tenfold increases in number of residents.

Some areas in the south and west also experienced significant population rise and this is especially visible in the central Co. Galway and in east Co. Cork. Similarly to Dublin, while the population within cities experienced some degree of decline, the suburbs and metropolitan areas have shown very sharp increases.

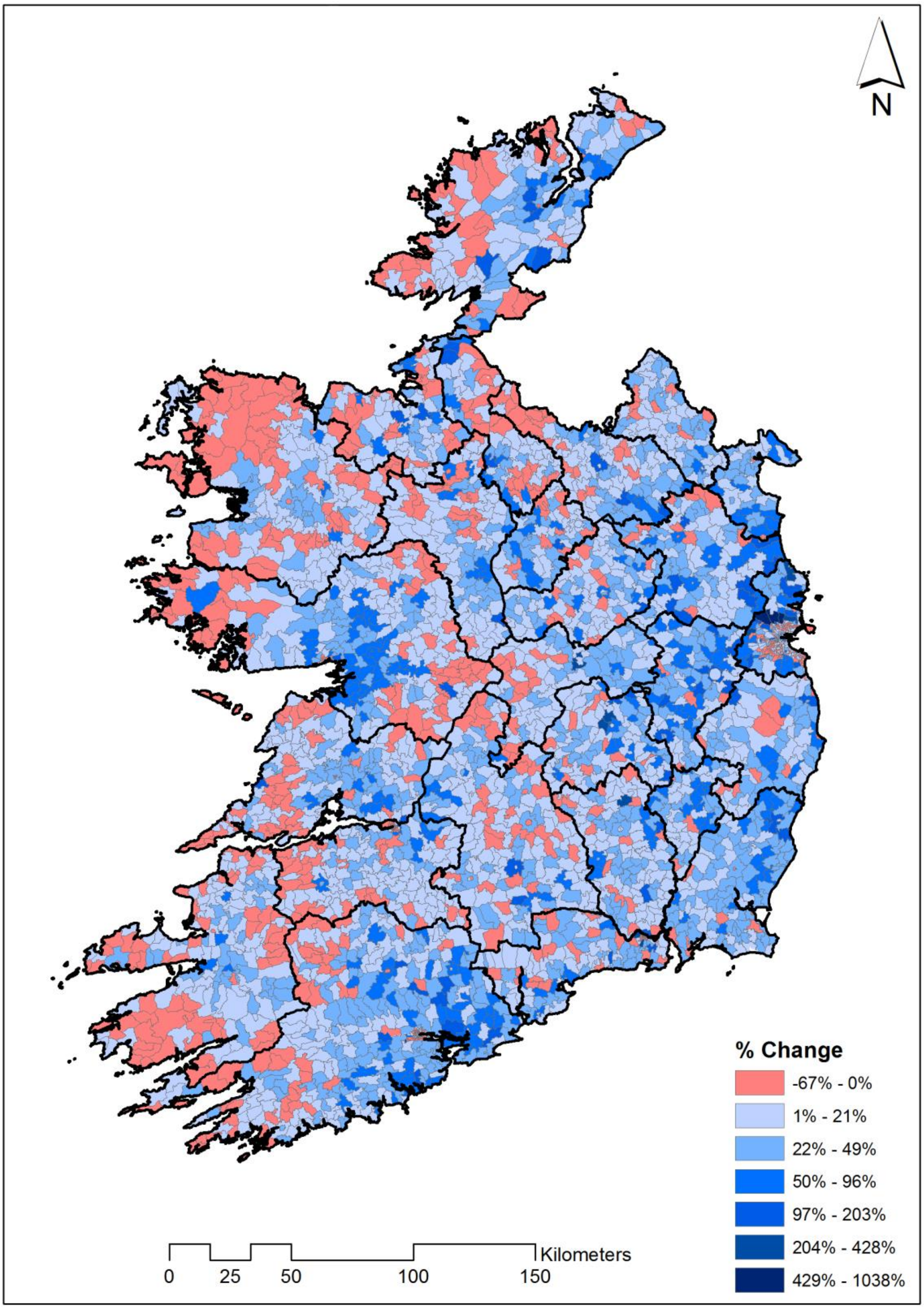

Fig 26. Population change map of Ireland showing percentage of change in the number of residents within each electoral division (ED).

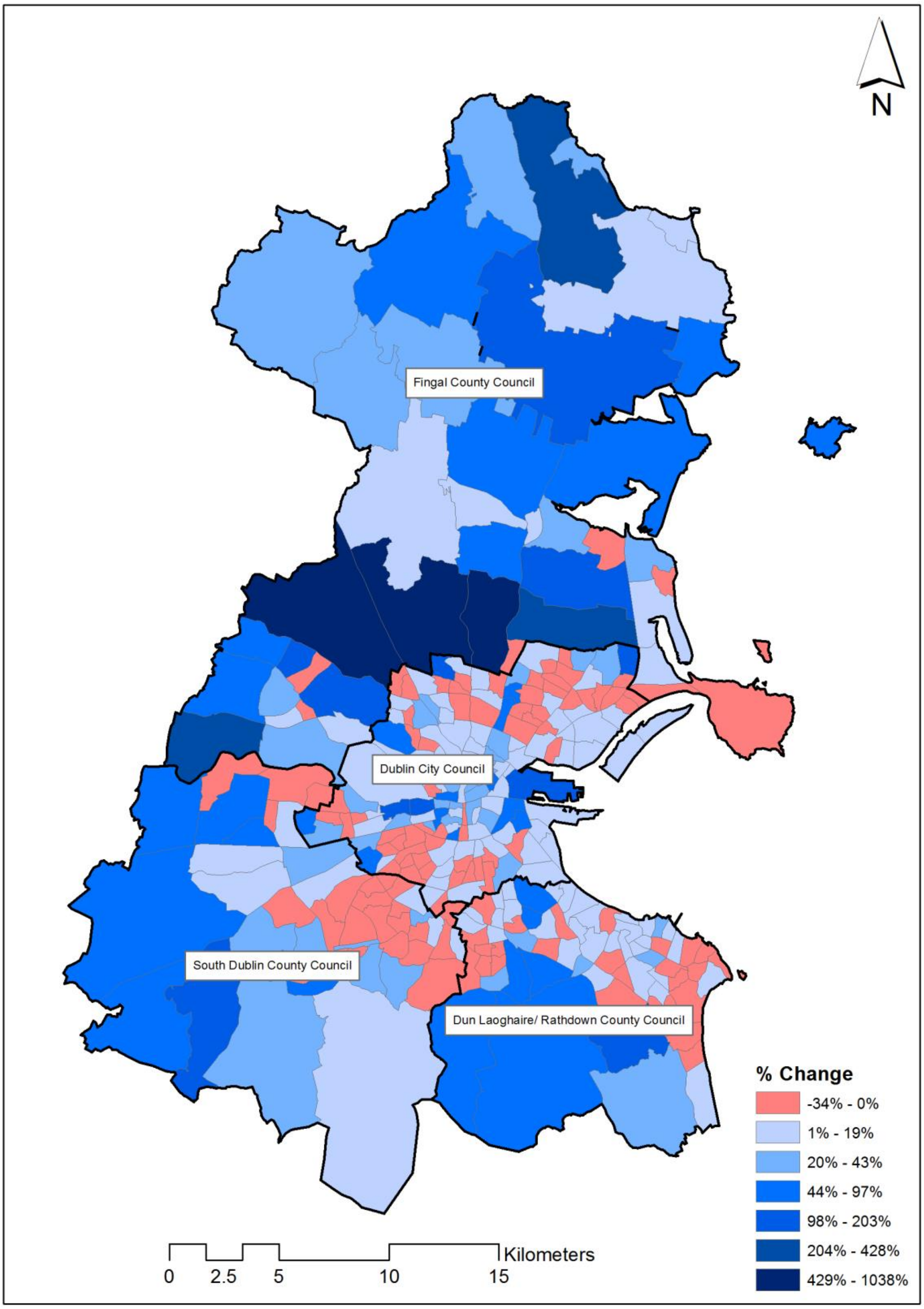

Fig 27. 2002 - 2016 population change in county Dublin by electoral division (ED).

5.7 Economic growth and development

Despite a dip corresponding with the recession of 2008, the GDP rates per capita have more doubled between 2000 and 2017 (see figure 28). Numbers within each bar represent change from previous year. A steady rise occurred up to 2007 with annual increase rates varying from 10.7% to 3.6%, until 2008 when the economy crashed and the GDP began falling. Negative rates occurred in 3 consecutive years before the GDP began slowly recovering in 2011. The two years with the most negative rates were 2008 and 2009 at -6.7% and -10.3% respectively.

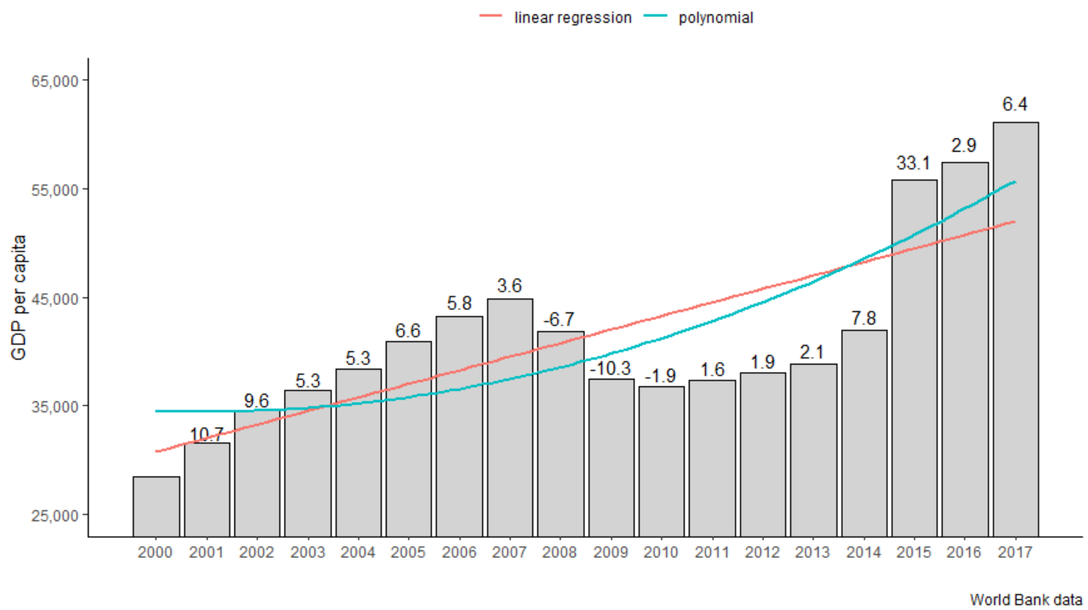

Figure 28. Per capita gross domestic product (GDP) growth in Ireland expressed in current local currency units, also fitted with a linear regression model indicating trend. Numbers above each bar represent percentage change from previous year.

2011 through 2014 were years of slow but steady recovery, bringing the GDP to its 2005 - 2006 pre-crash level. Remarkably, in 2015 the GDP grew 33.1% compared to 2014, bringing its value up to approximately €55,000, while the pre-crash peak occurred in 2007 at approximately €45,000. This jump was attributed by OECD (2016) to several multinational corporations moving their business and its underlying intellectual property to Ireland, hence assigning all their profits to the Irish GDP. In the next two years, albeit at a much lower rate, Irish per capita GDP continued to increase and in 2017 stood at over €61,000- a 114.6% increase on the 2000 value. During the same period, due to economic growth combined with a large population increase, the total GDP of Ireland has nearly tripled from €108.38bn in 2000 to €294.11bn 2017 (a 171.4% increase; World Bank 2019b).

5.8 Loss normalization

As others have discovered in similar studies, the rising trends in overall losses can be largely reduced (Schmidt *et al*. 2009) or nullified (Changnon *et al.* 2000, Bouwer *et al*. 2007, Pielke Jr *et al*. 2005, Bouwer 2019) when societal change and economic growth are taken into consideration. In similar fashion, this research concludes that the discovered positive linear trend in overall losses from weather extremes in Ireland is neutralized when loss values are adjusted for changes in population and per capita GDP (Figure 29).

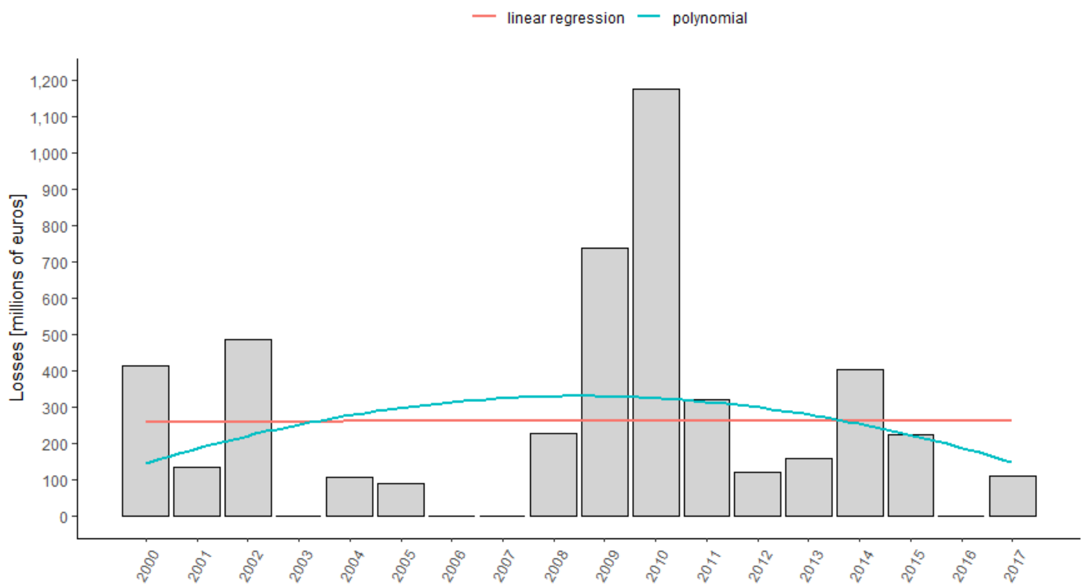

Figure 29. Normalized losses including adjustments for inflation, population change and economic growth. Fitted linear regression model shows no trend.

6. Discussion and conclusions

6.1 Frequency and magnitude of weather extremes

Although this research finds a rising trend in the frequency of extreme weather events in Ireland, the interannual weather variability might have biased this finding given the relatively short study period (Bouwer 2011). Trend analysis of an expanded timeseries is needed for a more definitive answer, although linear regression model and polynomial function fitted to Munich Re's NatCatSERVICE 1980 - 2017 dataset (figure 30) both show an even steeper increase in the frequency of weather extremes in Ireland. Elsewhere, there seems to be no scientific consensus regarding the increasing frequency of extreme events. While some researchers who's work spanned longer periods (Changnon *et al*. 2000, Pielke Jr *et al.* 2005) found no upward trends in the record of weather and climate extremes, others indicated significant increases in their frequency (Höppe and Grimm 2009). Bouwer (2019) points out that events of convective nature such as hailstorms and thunderstorms are likely to become more frequent with the rising temperatures, at the same time reminding that the (2012) IPCC report found evidence of such increase in the observed records to be insufficient.

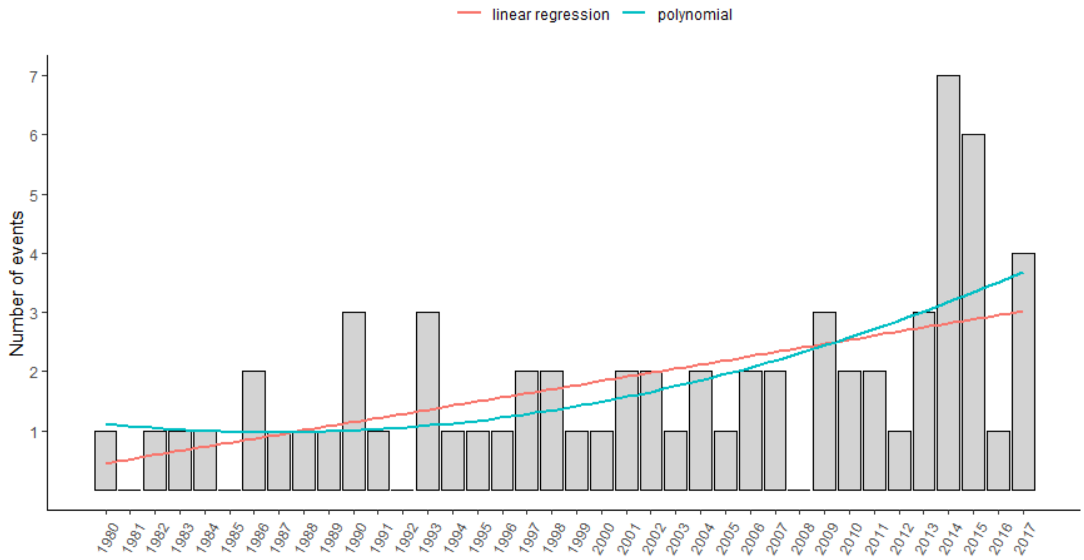

Fig 30. Frequency of extreme weather events in Ireland based on the 1980 - 2017 NatCatSERVICE dataset by Munich Re (natcatservice.munichre.com).

While much research (Schmidt *et al.* 2009, Changnon *et al*. 2000, Pielke Jr *et al*. 2005) has been carried out to evaluate the changes in frequency of weather extremes, Höppe and Grimm (2009) have also considered changes in their magnitude. Upon analysis of historical records, they found a significant increase in major hurricanes (3-5 SSHWS). Although beyond the scope of this work, a similar study could be carried out in Ireland i.e. regarding changes to the intensity of floods based on their estimated return periods. Where possible, return periods from secondary sources were recorded for the events included in this work, nevertheless they were encountered only for 8 out of 19 events and differed in their estimation methods.

Climate attribution studies facilitate better understanding of the frequency and magnitude of extreme weather and climatic events. With continued improvements to data and climate models anthropogenic forcing in a particular event can be ever more accurately quantified (Zhai *et al.* 2018). To date no such studies have been completed in Ireland, although results of a pioneering research to develop tools for climate attribution specific to Ireland are forthcoming (Leahy et al. in review).

6.2 Rising losses and their attribution

In agreement with research carried out in the United States by Changnon *et al.* (2000) and globally by Bouwer *et al.* (2007), this research initially finds losses from weather extremes in Ireland to be increasing. Although the increase in losses was much less dramatic than those identified in the US and globally, they emerged from a study spanning a much shorter period of time. Both Changnon's (*et al.* 2000) and Bouwer's (2007), as well as various other studies (Neumayer and Barthel 2011, Bahinipati and Venkatachalam 2016, Zhou *et al.* 2013) established that the upward trends in losses are nullified when adjusted for societal factors and economic growth and here too the case of Ireland is no different. Even despite the increase in the number of events, no trend in losses is apparent after normalization. Societal change and economic development are also identified as the leading cause of the rising cost of extreme weather events by other scientists (Bouwer 2019, Pielke Jr *et al*. 2005, Schmidt *et al*. 2009, Bruce 1999, Mills 2005, Huggel *et al.* 2013).

If increasing population densities and wealth accumulation have not yet significantly contributed to higher losses from extreme events in Ireland, they are likely to drive them in the future (Bouwer 2011 and 2013). Larger population densities mean more people to be potentially affected by an event, and higher GDP means more wealth exposed to damages. Also, as noted by Bruce (1999) and very relevant in the case of Ireland, land use change is an important factor when it comes to flooding. Urban development in river catchments not only exposes more people and assets to harm but reduces lands capacity to absorb and hold water during flooding. This was particularly apparent in Ireland during the flooding event of 2009 when many developments from the *Celtic Tiger* era built on river Lee's floodplains were inundated (Brennan 2017). Yet there are plans to redevelop another low-lying, poorly drained and prone to flooding area of the city in docklands (Jeffers 2011). Since floods are the most frequent and hence overall the costliest weather extreme experienced in Ireland and given climate models predicting future increases of winter stream flows, future losses from this particular weather disaster are likely to exacerbate. Moreover, all major cities in Ireland (Dublin, Cork, Limerick, Galway, Waterford) are situated on the coast and have major rivers passing through them, which makes them especially vulnerable to storms as well as flooding (fluvial, pluvial and coastal). Furthermore, continuous development and rising urban populations expose larger number of people and assets to potential damages. The population of Fingal, Co. Dublin has increased 50.7% between 2002 and 2016. That's almost 100,000 new residents in a coastal urban area vulnerable to extreme weather.

Increasingly more publications (Mechler and Bouwer 2015, Zhou *et al.* 2013, Bahinipati and Venkatachalam 2016, Huggel *et al.* 2013) on losses from extreme weather events emphasize the importance of accounting for the implemented adaptation and risk reduction measures in loss normalization methodologies. Mechler and Bouwer (2015) point out that accounting for exposure while ignoring vulnerability of people and assets may lead to overestimating future losses under climatic change. In addition, Neumayer and Barthel (2011) remark that loss normalization algorithms include changes in wealth over time but do not regard its dynamic spatial distribution. Huggel *et al.* (2013) reiterate the importance of availability of data on all drivers of risk (vulnerability, exposed asset value, probability and intensity) and the importance of incorporating these into loss attribution research framework. Loss and damage attribution studies should also contribute towards effective adaptation measures, by informing policymakers which investments will result in highest risk-reduction (Huggel *at al.* 2013).

6.3 Possibilities for future research

Research on extreme weather events in Ireland, losses they generate, and their attribution is scarce and leaves a lot of room for future inquiry.

To draw more definitive conclusions in terms of trends in the frequency of weather extremes and their associated economic losses analysis of datasets spanning longer time periods is required. Literature reviewed in chapter 2 would suggest 30 years as a minimum timespan for such studies and ideally as long as possible. Furthermore, systematic inquiry into the frequency and cost of a single type of weather extreme could yield different results than this study, where individual signals are obfuscated by the joint analysis of multiple types of events.

Scarcity of systematic weather data records in Ireland often forbids discussing individual events in their relevant and long-term context. Availability of data also dictated the themes for the maps in chapter 4.

Moreover, improved loss normalization algorithms taking into account adaptation and risk reduction measures or spatial distribution of wealth are increasingly becoming a scientific standard and would provide a greater insight into the dynamics of economic losses from extreme weather events in Ireland.

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Appendix A

Winter 2012 – spring/summer 2013 fodder crisis

TYPE OF EVENT:	Fodder crisis
RETURN PERIOD:	N/A
EXTENT:	Countrywide, worst in the west.
IMPACTS:	Huge economic cost of purchasing and importing from conserved forage from abroad and further millions of euros lost in reduced economic output due to dead and prematurely slaughtered animals which the farmers were unable to feed. Additional cost resulting from increased need for fertiliser later in the year to enhance grass growth and replenish fodder stocks.
DAMAGES:	€500m unadjusted
FATALITIES:	23,000 livestock animals.
EVENT NARRATIVE:	Extremely wet and also dull and cool summer of 2012 resulted in late and poor silage harvest. Many farmers experienced fodder shortages already in the late fall of 2012. A long winter followed by a very cold and also dull spring deepened the fodder deficit at most farms. Highly anticipated turnout of cattle to relieve the pressure came late and the grass growth was poor. Heightened need for supplementary feed and imported fodder resulted in higher than usual production costs and hence significantly lower incomes at most farms that year.
KEYWORDS:	Fodder crisis, cold spell, rainfall, grass growth.

Meteorological situation

81% of the agricultural land in Ireland is dedicated to pasture, hay and grass silage in order to support a growing national herd of cattle, which in 2013 counted 6.9m cows (European Commission 2019, CSO 2019). The climate in Ireland favours grass growth, providing local and cheap feed for livestock. Spring and summer are the most productive months while autumn and winter are usually too dull, wet and cold to support much growth. Meteorological conditions vary between years and seasons, and so fodder stock management plays an important role in ensuring that sufficient feed is available year-round at farm level (Hurtado-Uria *et al*. 2013). Such a big number of livestock animals (despite limited stocking densities), dependent primarily on locally produced grass, is unsurprisingly vulnerable to both interannual and intra-annual fluctuations in grass growth, especially without proper forecasting and management practices on a national level in place.

The 2013 fodder crisis was not a result of one particular weather extreme or even a single extreme season in meteorological terms. It was rather triggered by a combination of consecutive seasons with conditions unfavourable to grass growth as well as lack of grass growth forecasting and fodder stock management on a national scale.

Summer 2012

Thanks to the Jet Stream remaining south of Ireland throughout the summer, the season's weather was unsettled with colder, duller and wetter than average conditions. The rainfall totals were above normal throughout the country, with many stations in the South and East recording well in excess of 200% of the long term average and some experiencing their wettest summer on record (Ahlstrom 2012, O'Carroll, 2012). The average temperatures were 0.5- 1^{o}C below average and the sunshine hours were down 10- 30% (Ahlstrom 2012). Overall it has been the worst summer in 26 years (Hayes 2012), and one of the worst in the recorded history (O'Carroll 2012).

Autumn 2012

A comparison of readily available data from eight synoptic stations across Ireland (Casement Aerodrome, Claremorris, Cork Airport, Dublin Airport, Malin Head, Roches Point, Shannon Airport and Valentia Observatory) shows that the Autumn of 2012 was much less extreme than the summer. In terms of rainfall the totals were much more in line with the long term averages and ranged from 69% of the LTA at Cork Airport to 128% at Casement Aerodrome. The seasonal temperatures were lower than normal at all eight stations, with a mean 1^{o}C departure from average.

Winter 2012/2013

Mean air temperature varied across the country during this generally cold and dull winter. In the West the temperatures were closer to their LTA values with some stations reporting slightly above normal values. The rest of Ireland experience mostly below average temperatures, with largest below-average deviations in the Midlands (up to -2.2^{o}C).

Except for a few stations particularly in the West, the rainfall totals were above normal values, with seasonal totals of up to 175% of the LTA (Met Éireann 2013a).

The sunshine hours were generally below normal, save for a selection of stations located on the Atlantic coast (Met Éireann 2013a).

Spring 2013

The spring of 2013 was likely the crucial season in triggering the fodder crisis. After a very bad summer of 2012 resulting in poor and late silage harvest, the winter fodder stocks were tight and many farmers were in deficit. Grass growth during the cold spring of 2013 was very poor and delayed the turnout of cattle, increasing the need for silage and concentrate feed (Teagasc 2013).

The 2013 spring was colder than average everywhere in Ireland, from around 1°C below average in April and May to about 3°C below average in March. It was the coldest March on record for most stations. Overall the sunshine hours were also below normal. Although April was slightly sunnier than usual everywhere, May was rather below average in most areas and March was very dull with the Eastern half of the country receiving only between 50 and 75% of its usual sunshine hours (Met Éireann 2013b, 2013c, 2013d and 2014d). Rainfall totals varied across the country. Midlands and parts of the West experienced 75- 100% of average while coastal areas generally received between 100 and 125% of the LTA (Met Éireann 2014d).

Impacts

The cold, dull and extremely wet summer of 2012 resulted in late and poor grass harvest. The first signs of fodder crisis came in November of the same year, when a third of Irish farmers were already in deficit of silage (Ahlstrom 2012, Teagasc 2013). Poor grass growth during the cold and rather dull spring, and late turnout of cattle increased the need to supplement the silage with concentrate feed to make the stocks last (Teagasc 2013). An average farmer used 15- 20% more concentrate and spent up to 40% more on purchased fodder than in 2012 (Hennessy *et al.* 2013). Moreover, the price of concentrate feed was significantly higher than usual at around €300/tonne. Very high prices achieved by beef in June 2013 could have offset some of those costs, however many farmers have sold or slaughtered their animals earlier in the year due to adverse circumstances (Mailey 2014).

The increased need for concentrate and its higher than usual price was responsible for most of the losses from the fodder crisis which were estimated to be in the region of €450m- €500m, however, with some long-term costs not being easily quantifiable this number may not be final (AgriLand.ie 2013, Murphy 2013b). There was also an increased need for fertiliser later in 2013 to rebuild exhausted fodder stocks; on an average beef farm the cost of fertiliser increased by €42/ha (Boyle 2014, Fay 2014). Altogether, some 40% of livestock farmers were badly hit by the fodder shortage, although there was a lot of variability throughout the country. The West and

Northwest were worst off with 80% of farmers affected, while far fewer struggled in the South (20-25%) and East (10-15%) of the country (Green *et al.* 2013). Annual incomes declined significantly at all types of livestock farms except dairy, where high milk prices and increased per hectare productivity made up for the increased costs of production and resulted in an overall increase (Cawley 2014). Sadly, 23,000 livestock animals died as a result of the forage shortage resulting in an economic loss of €17m. Many more animals were slaughtered prematurely and the financial losses due to the reduced weights and quality of beef are hard to quantify (AgriLand.ie 2013, Murphy 2013b).

Various agencies and state bodies provided assistance to the affected farmers. In April, minister Simon Coweney and the Department of Agriculture set up a €1m fund to lower the cost of imported fodder. Payments under the scheme were made through co-ops and on per bale basis between April 15th and May 3rd. The scheme was later extended until May 24th and the funding was doubled to €2m (Hynes 2013, Croffey 2013). Three Irish companies- SuperValu, Kepak and Oliver Carty Ltd, contributed €250,000 for relief payments which were administered by the IFA. SuperValu also offered their truck fleet to transport the imported forage arriving by sea within Ireland (O'Carroll 2013, Dermody 2013). The IFA set up additional €1.3m fund to cover the transportation expenses, taking this additional burden off farmers' shoulders (Barry 2013). Approximately 3,000 loads of conserver forage were imported into Ireland, mostly from the UK, France and the Netherlands (Donohoe 2014).

The magnitude of the crisis is well illustrated by the fact that grass for fodder was even harvested from the 200 acres of Dublin Airport grounds (BBC News 2013).

Prior to the 2012/2013 fodder crisis there were no grass growth monitoring and forecasting systems available in Ireland to help farmers plan ahead and manage their fodder stocks.

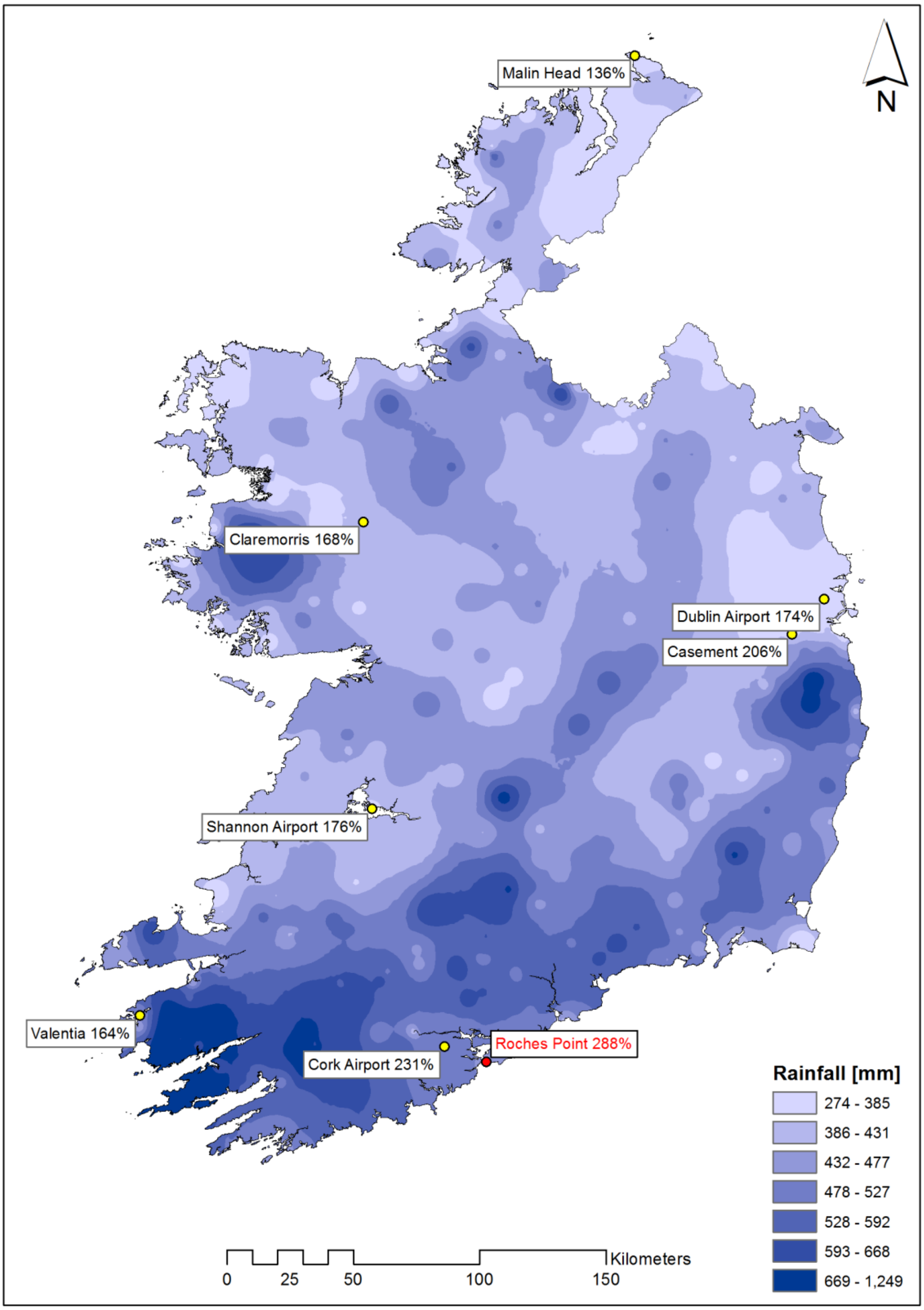

Fig 31. Summer 2012 total rainfall intensity and distribution with several locations labelled with their total summer rainfall as percentage of their respective LTA.