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SNOW LOADINGS AT 100M ABOVE MEAN SEA LEVEL IN IRELAND

Carla Mateus and Barry Coonan

Met Éireann, Glasnevin Hill, Dublin 9

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1. Introduction

The climate of Ireland is changing. Consequently, the Department of Housing, Local Government and Heritage funded this project to update 'Climate maps and data to support building design standards in Ireland'. The motivation of this research was to produce maps of the return levels of snow loads for the return periods of 50, 100 and 120 years for use in building design to enhance resilience in support of climate change adaptation in Ireland.

The outputs of this research will benefit a wide range of stakeholders currently collaborating with Met Éireann, such as the National Standards Authority of Ireland and the Department of Housing, Local Government and Heritage. This report will also inform policy in delivering key national infrastructures such as housing and building renovation.

1.1. Snow loading

The calculation and mapping of return values of snow loading for return periods of 50, 100 and 120 years are necessary for the structural design of buildings and civil engineering works (NSAI, 2015a,b). Specifically, the design of buildings will have to consider that snow can be deposited on a roof in different patterns (ISO, 2013; NSAI, 2015a,b). Snow loading information is also necessary for the design of bridges (e.g. BSI, 2007).

A previous snow loading map at 100m above mean sea level for a 50-year return period for Ireland had focused the calculations of the greatest snow depth per year based on daily observations from a small network of 10 stations and without stations from Northern Ireland (Keegan, 2010; Government of Ireland, 2012; NSAI, 2015b). Discrepancies were identified in the map produced for Ireland (Keegan, 2010; Government of Ireland, 2012; NSAI, 2015) with the map produced by BSI (2007) for the United Kingdom and Ireland for a 50-year return period. The discrepancies in the map for Ireland (Keegan, 2010; Government of Ireland, 2012; NSAI, 2015b) refer to an area of 0.7kN/m^2 in the Dublin/Wicklow area, higher snow loadings of 0.6kN/m^2 in the Monaghan region (Clones) and the Southern region represented as 0.4kN/m^2. As Keegan (2010) reported, the results should not be considered overly accurate due to the daily resolution of the snow depth observations, the small number of stations and the relatively few years with significant snow. Other snow loads maps at sea level were produced for the UK and Ireland (NSAI, 2015a).

In this report, Met Éireann employed the methodology described in NSAI (2015a) to produce maps of the return levels of snow loads at 100 meters above mean sea level for the return periods of 50, 100 and 120 years by applying a Generalised Pareto distribution (Coles, 2001; Gilleland and Katz, 2016). The snow loading maps produced in this research show improvements in comparison with the previous map (Keegan, 2010; Government of Ireland, 2012; NSAI, 2015b) and present more agreement with the preceding maps produced for the UK and Ireland (BSI, 2007) and are described as follows:

1. A total of 33 stations, including 19 stations across Ireland with between 33 and 80 years of data, plus 14 stations from Northern Ireland with between 16 to 64 years of quality-controlled snow depths observations, have been used to calculate the snow load return periods. A total of 13 stations had overlapping daily and hourly snow depth observations, generally from 1990 onwards. The hourly observations for 13 stations were assessed to determine the greatest snow depth per year.
2. The comparison of hourly and snow depth observations allowed the application of a more accurate correction of +3cm to account for a possible discrepancy between the once-daily recorded snow depth and the actual maximum snow depth over that particular day which can occur at any time over 24 hours. In contrast, Keegan (2010) applied a correction of +2cm.
3. Including stations from Northern Ireland in the data analysis in this research was necessary to avoid snow load discrepancies along the border region when compared to previous maps produced for the United Kingdom and Ireland by BSI (2007).
4. The map gridding methodology employed in R software in this research is more robust than the spline interpolation employed in ArcGIS to generate the previous map of snow loads (Keegan, 2010; Government of Ireland, 2012; NSAI, 2015b). Specifically, the interpolation of return

periods across all grid points is made in two processes: a linear regression of return periods with easting and northing as predictive power and a second step to interpolate the linear regression residuals across grid points using a weighted average of nearest stations to a particular grid point, known as inverse distance weighting (IDW).

5. Using a denser network of stations and longer data series in this research allowed the generation of more realistic maps of snow loading.

1.2. The climate of Ireland

Ireland is located between latitude 51°N and 56°N, longitude 5°W and 11°W in western Europe and at the eastern edge of the north Atlantic Ocean, and has an area of about 84,000km^2. The main mountains have peaks above 600m, and the Carrauntoohil in Co. Kerry is the highest mountain at 1041m above sea level, whereas the central plain is generally less than 150m above mean sea level. About 240km^2 lies above 600m above sea level, and about 4,100km^2 lies between 300 and 600m above sea level (Rohan, 1975, citing Roberts, 1967).

The climate of Ireland is marked as mild and maritime by the influence of the proximity to the Atlantic Ocean to the north, west and south and the Irish Sea to the east of the Island. Air temperature extremes in summer and winter are less intense than in more continental countries at similar latitudes due to the influence of the North Atlantic Current on the climate in Ireland.

In winter, snow often occurs when the cold continental air mass from the north or east meets the relatively mild and moist maritime air from the south or west. Moreover, distinct parts of Ireland are more affected by snowfalls associated with specific air masses. Some snowfalls can be localised. Specifically, snowfalls in the west and northwest are commonly associated with polar maritime and Arctic airstreams, which are related to frequent snow showers due to the convective activity and instability over the relatively warm seas. Occasionally significant snowfalls occur with blocking anticyclonic conditions to the north of Ireland, pushing the north Atlantic jet stream and associated storm systems south and bringing an easterly polar continental airflow. Eastern and midland areas are more affected under these conditions since these areas are prone to unstable north-easterly winds blowing onshore from relatively warm waters of the Irish Sea, which can often produce significant snowfalls such as the events that occurred in 1947, 1987, 2009, 2010 and 2018. The heavy snowfall events associated with storm Emma and the cold spell between the 28th of February and the 4th of March of 2018 and dubbed the 'Beast from the East' occurred as the moisture-rich air associated with the storm met the sub-zero temperature air mass, which had become established over Ireland. Persistent and strong negative phases of the Arctic Oscillation and North Atlantic Oscillation have been associated with cold spells with snow events, such as during the winter of 2010.

Snow in Ireland has occurred in any of the months from November to April, although snow is more frequent in the months from December to March. Snow has also been reported in May and September, and some falls have been considerable; however, snow tends to melt quickly in these months (Rohan, 1975). The occurrence of significant snow depths is reasonably rare except on higher ground; however, there are many references to historical occurrences of major snowfalls in Ireland (e.g. Dixon, 1953; Murphy, 2012). The depth of snow lying on the ground is often no more than a few centimetres and does not last long. However, there have been registered snow depths exceeding 30cm on low ground at inland stations (e.g. Murphy *et al*., 2019). On the 3rd of March of 2018, a snow depth of 69cm was registered at Glenmacnass in Co. Wicklow. In general, snow cover at locations near the sea level lasts on the ground for a day or two because of the warm ground surface, namely in the western and southern areas. Often the snow is mixed with rain while falling and melts almost as quickly as it falls at locations near sea level. In contrast, locations in the eastern and northeastern interiors have a greater number of days with snowfall. The occurrence of snow tends to increase with distance from the west and south coasts, and snow lying is more often recorded in the midlands and eastern areas than in the west part of the country due to an easterly polar continental airflow, where the jet stream has been pushed south. Snow lasts longer on the ground and is more frequent in the north since the temperature decreases with increased latitude. The number of days with snow cover tends to increase northwards through the midlands, corresponding to the decrease in winter air temperatures. Some of the more remarkable snowfalls had snow lying on the ground lasting 10 to 12 days (Murphy, 2012).

A snow depth of at least 2cm is likely in most places every two years. In contrast, falls of at least 10cm occur every 7 to 19 years at locations in the midlands and in the north midlands about once every 6 to 7 years (Murphy, 2012). The number of days with snow cover is variable from year to year. Many places have several years free from major snowstorms or even light snowfall events.

Due to the infrequent and irregular occurrence of significant events, snow depths in large quantities cause severe disruption. Major snowfall events can disrupt road traffic, rail and air travel, work and school closures, water shortages and damage to overhead power and communication lines (e.g. Moore *et al*., 2019).

2. Methodology

The standard I.S. EN 1991-1-3:2003&AC:2009&A1:2015 (NSAI, 2015a) was used to produce maps of the return levels of snow loads for return periods of 50, 100 and 120 years for Ireland. This section sets out the meteorological data used, the calculation of return levels of snow depths for return periods of 50, 100 and 120 years based on the Generalised Pareto distribution, the adjustment from the once-daily to hourly observations of snow depths, conversion of snow depths to snow loads, the adjustment of snow loadings to a 100m above mean sea level reference altitude and the gridding techniques to produce the maps. A total of six classes ranging from <0.3 to 0.7 – 0.8kN/m^2 are employed in the maps of the return values of snow loadings for return periods of 50, 100 and 120 years for Ireland.

2.1. Snow depths data

A total of 33 stations with quality-controlled daily snow depth observations for the Island of Ireland were employed in the data analysis (Figure 1, Table 1). The annual maxima of daily snow depth observations from 19 stations across Ireland with between 33 and 80 years of data, plus 14 stations from Northern Ireland with between 16 to 64 years of data, have been used to calculate the snow load return periods (Table 1). A total of 13 stations had overlapping daily and hourly snow depth observations generally from 1990 onwards. The hourly observations for 13 stations were assessed to determine the greatest snow depth per year (Table 1).

Systematic snow depth observations have been taken at the synoptic stations in Ireland since 1942. Observations of snow depths can be affected by drifting. Drifts of six meters or more have been reported in hilly areas; in flat countryside, drifting can occur near buildings or fences (Murphy, 2012). Thus, snow depth observations are taken at points estimated to be relatively free of drifting. The meteorological instruments, methods of observation, and quality-control procedures of the meteorological observations follow the international standards stipulated by the World Meteorological Organization (2018a,b). The observations from Ireland were obtained from the National Climate Archive at Met Éireann. With regards to the stations from Northern Ireland (Figure 1, Table 1), the daily (Met Office, 2021a) and hourly (Met Office, 2021b) snow depth observations were downloaded from the CEDA Archive.

For stations in Ireland, the snow depth observations are defined as follows:

- **Hourly snow depth:** Snow depth observations in centimetres observed in the 24 hours from 00:00 to 23:00 hours.
- **Daily snow depth**: Manual snow depth observations in centimetres from synoptic and climate stations. The once-daily observation times were taken at 09:00 in the climate stations. In the case of the synoptic stations, the snow depths were reported at the main hours of 06:00 and 09:00 and also recorded on hourly synoptic observations if snow depths were present.

For stations in Northern Ireland, the snow depth observations are defined as follows:

- **Hourly snow depth:** Snow depth observations in centimetres observed in the 24 hours from 00:00 to 23:00 hours.
- **Daily snow depth**: Snow depth observations in centimetres and registered once-daily at 09:00.

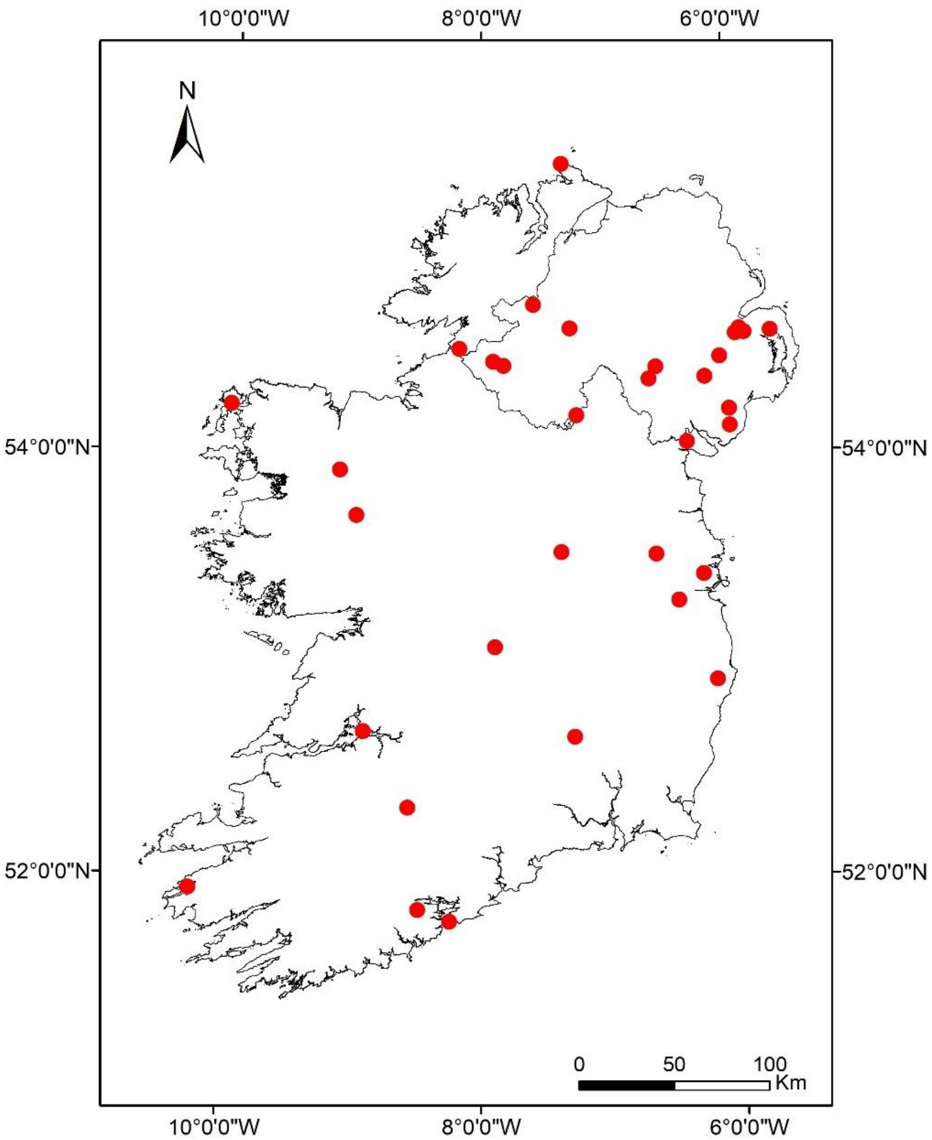

Figure 1: Location of the stations with snow depth observations on the Island of Ireland.

Table 1: Meteorological stations and respective elevation, geographical coordinates, data resolution and period covered by the snow depth observations on the Island of Ireland. Stations located in Northern Ireland are marked with an asterisk (*). In case of re-location of the station or replacement from manual to automatic station, the geographical coordinates correspond to the most recent location.

Name	Latitude (°)	Longitude (°)	Data resolution	Period	Years
*Armagh	54.35200	-6.65000	Daily	1959 – 2022	64
Ballyshannon (Cathleen's Fall)	54.49833	-8.17583	Daily	1966 – 2022	57
*Ballywatticock	54.57200	-5.65700	Daily	1974 – 2010	37
*Belfast Newforge	54.56000	-5.94100	Daily	1982 – 2020	39
*Belfast Ravenhill Road	54.58400	-5.91000	Daily	1986 – 2020	35
Belmullet	54.22780	-10.00690	Daily	1957 – 1989	55
			Hourly	1990 – 2011	
Birr (merged with Gurteen)	53.09030	-7.89028	Daily	1955 – 1989	67
			Hourly	1990 – 2009	
Gurteen	53.03500	-8.00861	Daily	2010 – 2021	
Casement	53.30556	-6.43889	Daily	1962 – 1989	60
			Hourly	1990 – 2021	
*Castlederg	54.70700	-7.57700	Daily	2006 – 2007 2012	15
			Hourly	2008 – 2011 2013 – 2020	
*Castlereagh	54.56500	-5.87100	Daily	1990 – 2020	31
Claremorris	53.71111	-8.99139	Daily	1950 – 1989	63
			Hourly	1990 – 2012	
Clones	54.18330	-7.23330	Daily	1951 – 1989	60
			Hourly	1990 – 2010	
Cork Airport	51.84722	-8.48611	Daily	1962 – 1989	60
			Hourly	1990 – 2021	
*Derrygonnelly	54.41800	-7.82100	Daily	2002 – 2017	16
Dublin Airport	53.42778	-6.24083	Daily	1942 – 1989	80
			Hourly	1990 – 2021	
Dundalk (Annaskeagh W.W.)	54.05190	-6.35139	Daily	1974 – 2016	43
*Edenfel	54.59400	-7.28300	Daily	1981 – 2016	36
Glenealy (Kilmacurragh Park)	52.92917	-6.14972	Daily	1982 – 2019	38
*Hillsborough	54.45300	-6.07300	Daily	1959 – 2020	62
Kilkenny	52.66530	-7.26944	Daily	1958 – 1989	51
			Hourly	1990 – 2008	
*Loughgall no 1	54.40800	-6.60400	Daily	1959 – 1995	53
*Loughgall no 2	54.40800	-6.59200	Daily	1995 – 2011	
*Lough Navar Forest	54.43900	-7.90100	Daily	1961 – 2020	60
*Magherally	54.35900	-6.19600	Daily	1977 – 2020	44
Malin Head	55.37222	-7.33889	Daily	1956 – 1989	66
	55.37222	-7.33889	Hourly	1990 – 2010	
	55.37194	-7.33917	Daily	2011 – 2021	
Mount Russell	52.32970	-8.56917	Daily	1990 – 2022	33

Table 1: Continued.

Name	Latitude (°)	Longitude (°)	Data resolution	Period	Years
Mullingar	53.53720	-7.36222	Daily	1950 – 1989	72
			Hourly	1990 – 2008	
			Daily	2009 – 2021	
Roches Point	51.79306	-8.24444	Daily	2005 – 2021	17
Shannon Airport	52.69028	-8.91806	Daily	1946 – 1990	76
			Hourly	1991 – 2021	
*Silent Valley	54.12700	-6.00200	Daily	1977 – 2020	44
Straide	53.92500	-9.12639	Daily	1984 – 2019	36
*Trassey Slievenaman	54.20600	-6.00600	Daily	1985 – 2020	36
Valentia Observatory	51.93806	-10.24330	Daily	1940 – 1989	72
			Hourly	1990 – 2011	
Warrenstown	53.52440	-6.61111	Daily	1961 – 2015	55

2.2. Calculation of return periods

Extreme values are scarce, and the estimation of extremes for levels such as 50, 100 and 120 years implies an extrapolation from instrumental observations to unobserved levels, and extreme value theory allows a class of models to enable such extrapolation (Coles, 2001).

The daily snow depth observations were assessed to determine the highest snow depth per year. When both daily and hourly observations were available for the same period, the hourly observations were examined to ascertain the highest snow depth per year. A Generalised Pareto distribution was fitted to the series of the greatest snow depths per year to produce the return levels of snow depths for each station for 50, 100 and 120 years return periods. A Generalised Pareto distribution fitting algorithm was implemented using the extreme value analysis R package extRemes 2.0, which has a focus on climate applications (Gilleland and Katz, 2016)

A Generalised Pareto distribution was applied to calculate return levels from a series of the greatest annual snow depths with potentially many zeros (representing years without snowfall events). Specifically, significant snowfall events across the Island of Ireland are reasonably rare, with many of the annual maximum snow depth observations from lower-lying and southerly located stations, in particular, showing a high proportion of no snow years. For instance, over the 72-year snow record of Valentia Observatory, only 20 years had snow depth observations, with most of the values being light snow depths. Also, over the 76-year snow record of Shannon Airport, only 28 years present light snow depth observations.

Regarding the selection of thresholds, inference includes fitting the Generalised Pareto distribution to the observed threshold exceedances, followed by model verification and extrapolation. The Generalised Pareto distribution is distinct from the block maxima method by characterising an instrumental observation as extreme if it exceeds a higher threshold (Coles, 2001). The threshold selection requires a balance between bias and variance: a threshold too low is likely to violate the asymptotic basis of the model, resulting in bias, whereas a threshold too high will produce few excesses with which the model can be estimated, leading to high variance (Coles, 2001). Therefore, the standard practice is to choose a low threshold as possible and subject to the limit model proving a reasonable approximation (Coles, 2001). To this end, mean residual life plots are interpreted, and the Generalised Pareto distribution is fitted to a range of thresholds to assess the stability of parameter estimates (Coles, 2001). This process is cross-referenced with the three greatest snow depth observations registered on the instrumental record for each station. In this case, the Generalised Pareto distribution sets a threshold below which data is ignored, removing years when no snow or very little snow is recorded, and fitting to the remaining dataset. This threshold can be set to optimise the fit between the observed data and model and thus improve the confidence in the return periods calculated.

2.3. Adjustment for the once-daily versus hourly observations

A once-daily snow depth observation will likely occasionally miss the highest snow depth compared to hourly observations over a 24h period. Therefore, the once-daily snow depth observation can underestimate the maximum snow depth on that particular day. However, the analysis of the overlapping once-daily and hourly observations of snow depths for 13 stations quantified this discrepancy. Once-a-day snow depth observations are available at 33 locations with lengths of record ranging from 16 to 80 years. Hourly observations are obtainable for 13 stations, typically starting from 1990 for most of the stations in Ireland.

In 36% of cases where the snow depth was greater than zero, the daily and hourly measured maximum snow depths were the same. In 95% of cases, the daily snow depths were within -3cm of the hourly maximum for that particular day. A +3cm adjustment was added to the daily snow depths to adjust the discrepancy between daily and hourly snow depths across all stations.

2.4. Adjustment of return period snow depths to 100m elevation

Snow depths increase with altitude. An adjustment is made to the return period snow depths of stations to produce an equivalent value at a standardised elevation of 100m above mean sea level. This adjustment is based on the distribution of station altitudes and snow depths for each return period using a linear regression fit of the snow depth versus elevation. The correction for stations used here is 9.4cm per 100m for the 50-year return period snow depths, 11cm per 100m for the 100-year return period snow depths and 11.4cm for the 120-year return period snow depths. For example, the 100-year return period snow depth for a station at 50m elevation will be adjusted up by 5.5cm, whereas a station at an elevation of 200m will have its 100-year return period snow depth reduced by 11cm.

BSI (2007) suggests a variation of 0.2kN/m^2 in snow load for every 100m of height for use in the UK and Ireland regions. This is equivalent to a 10cm snow depth adjustment.

2.5. Adjustment for snow loadings at 100m above mean sea level

In order to convert the 50, 100 and 120 years return periods of snow depth to snow loading, the density of the snow must be known. A figure of 2.0 kN/m^3 is appropriate for snow which is 'settled (several hours or days after its fall)' (Keegan, 2010). Therefore, the conversion from snow depth to snow load is the following:

1cm of snow depth = 0.02kN/m^2 of snow loading (*Equation 1*)

2.6. Gridding

In order to produce a map based on a limited number of point sources of observation (weather stations), the return values need to be interpolated across the entirety of the grid to be mapped, a technique which is described as gridding (e.g. Dyer and Mote, 2006). Here we use a 1km^2 grid covering the Island of Ireland, which is based on the Irish National Grid (TM75 https://epsg.io/29903-1956).

The interpolation of return values across all grid points is carried out in two steps. First, a linear regression of the return value to be interpolated, the 50-year return value of snow load, for example, versus geographical variables of the observation points or weather stations, is performed. These geographical variables include the stations' position (easting, northing), distance from the sea, exposure to the sea and elevation (Walsh, 2016). However, only easting and northing were found to have useful predictive power, Pearson R^2 correlation > 0.2, so they were the only geographical variables used to fit the snow loads data. Here the linear regression would look like this:

$$SLRP_p = SLRP_{mean} + a_1\boldsymbol{easting} + a_2\boldsymbol{northing} + \boldsymbol{residual} \quad (Equation\ 2)$$

where $SLRP_p$ is the predicted snow load return period, $SLRP_{mean}$ is the mean of the snow load return period across all stations, *easting* and *northing* are the coordinates of the grid point and $a_{1,2}$ are the values multiplying the geographical variables in order to get the best fit for the observation parameter.

The second step interpolates the linear regression residuals across grid points using a weighted average of the nearest stations to a particular grid point, a technique known as inverse distance weighting (IDW) (e.g. Chen and Liu, 2012; Burrough and McDonnell, 2015). The R package gstat is used to interpolate the residual values across the grid points (Walsh, 2016).

The final grid point interpolation/prediction is based on equation 3:

$$SLRP_p = SLRP_{mean} + a_1\boldsymbol{easting} + a_2\boldsymbol{northing} + IDW(\boldsymbol{residual}) \quad (\textit{Equation 3})$$

The described gridding methodology has been widely employed by Met Éireann, such as in generating official climate normals (e.g. Walsh, 2016).

3. Results

The return values of snow depth in centimetres for return periods of 50, 100 and 120 years and a comparison with the greatest three snow depths per year on record for stations in Ireland are presented in Table 2. The return period snow depths in centimetres adjusted to 100m elevation for stations in Ireland are shown in Table 3. **The return periods of 50, 100 and 120 years of snow loadings in kN/m^2 at 100m above mean sea level, including the 3cm hourly to daily correction, are presented in Table 3.**

The geographical distribution of the return values of the 50-year return period of snow loadings in Ireland presents four classes spread diagonally: <0.3, 0.3 – 0.4, 0.4 – 0.5 and 0.5 – 0.6kN/m^2 (Figure 2). The lowest class, <0.3kN/m^2, is presented in parts of the counties Kerry and Cork. The 0.3 – 0.4kN/m^2 class is distributed in Care, Limerick, Kilkenny, Tipperary and Waterford and parts of Carlow, Cork, Galway, Kerry, Laois, Mayo, Offaly and Wexford. The 0.4 – 0.5kN/m^2 class is represented in the counties Kildare, Leitrim, Longford, Roscommon, Sligo, Westmeath and Wicklow and parts of Cavan, Carlow, Donegal, Dublin, Galway, Laois, Mayo, Meath, Monaghan, Offaly and Wexford. The highest class of 0.5 – 0.6kN/m^2 is distributed in parts of Cavan, Donegal, Dublin, Louth, Meath and Monaghan.

The geographical distribution of the return values of the 100-year return period of snow loadings in Ireland has four classes ranging from the lowest at 0.3 – 0.4kN/m^2 to the highest at 0.6 – 0.7 kN/m^2 (Figure 3). The 0.3 – 0.4kN/m^2 class only covers parts of Cork, Clare Kerry and Limerick. The 0.4 – 0.5kN/m^2 class is distributed in Kilkenny, Tipperary and Waterford and parts of Carlow, Clare, Cork, Galway, Laois, Limerick, Mayo, Offaly, Roscommon, Westmeath and Wexford. The 0.5 – 0.6kN/m^2 class is spread in Kildare, Leitrim, Longford, Sligo and Wicklow and parts of Cavan, Carlow, Donegal, Dublin, Galway, Laois, Mayo, Meath, Offaly, Roscommon, Westmeath and Wexford. The highest class of 0.6 – 0.7kN/m^2 is distributed in Louth and parts of Dublin, Donegal, Cavan, Meath and Monaghan.

The geographical distribution of the return values of the 120-year return period of snow loadings in Ireland has five classes ranging from the lowest at 0.3 – 0.4kN/m^2 to the highest at 0.7 – 0.8kN/m^2 (Figure 4). The 0.3 – 0.4kN/m^2 class covers parts of Cork and Kerry. The 0.4 – 0.5kN/m^2 class is spread in parts of Clare, Cork, Galway, Kerry, Limerick, Tipperary and Waterford. The 0.5 – 0.6kN/m^2 class is distributed in Kilkenny and parts of Carlow, Clare, Galway, Kildare, Laois, Leitrim, Limerick, Longford, Mayo, Offaly, Roscommon, Sligo, Tipperary, Waterford, Westmeath, Wexford and Wicklow. The 0.6 – 0.7kN/m^2 class covers Cavan, Dublin Meath and Monaghan and parts of Carlow, Donegal, Kildare, Leitrim, Longford, Louth, Offaly, Roscommon, Sligo, Westmeath, Wexford and Wicklow. The highest class of 0.7 – 0.8kN/m^2 only covers parts of Donegal and Louth.

Table 2: Return values of snow depth in centimetres for return periods of 50, 100 and 120 years and comparison with the greatest three snow depths per year on record for stations in Ireland.

Name	Greatest three snow depths (cm) per year on record			Period	Years	Return periods		
	1st	2nd	3rd			50-year (cm)	100-year (cm)	120-year (cm)
Ballyshannon (Cathleen's Fall)	15	12	10	1966 – 2022	57	14.8	18.1	18.9
Belmullet	17	8	7	1957 – 2011	55	12.9	15.5	16.2
Birr (merged with Gurteen)	13	12	12	1955 – 2021	67	14.1	15.5	15.8
Casement	45	30	27	1962 – 2021	60	38.1	47.2	49.7
Claremorris	20	18	13	1950 – 2012	63	19.4	21.5	22.0
Clones	25	20	15	1951 – 2010	60	22.6	25.6	26.3
Cork Airport	26	16	15	1962 – 2021	60	21.5	25.9	27.0
Dublin Airport	25	23	20	1942 – 2021	80	22.5	25.6	26.4
Dundalk (Annaskeagh W.W.)	17	9	7	1974 – 2016	43	15.8	18.0	18.6
Glenealy (Kilmacurragh Park)	24	8	4	1982 – 2019	38	18.3	24.3	25.8
Kilkenny	18	14	10	1958 – 2008	51	17.2	19.6	20.2
Malin Head	38	8	7	1956 – 2021	66	17.8	22.5	23.7
Mount Russell	19	17	16	1990 – 2022	33	21.9	24.2	25.0
Mullingar	18	15	14	1950 – 2021	72	18.2	19.6	19.9
Roches Point	10	9	8	2005 – 2021	17	12.5	12.7	12.8
Shannon Airport	6	5	4	1946 – 2021	76	8.1	8.7	8.8
Straide	15	12	11	1984 – 2019	36	16.7	17.9	18.1
Valentia Observatory	12	5	5	1940 – 2011	72	8.8	10.8	11.4
Warrenstown	21	18	5	1961 – 2015	55	16.5	26.7	30.2

Table 3: Station elevation and return period snow depths in centimetres adjusted to 100m elevation for stations in Ireland shown in the first columns. The return periods of 50, 100 and 120 years of snow loadings in kN/m² at 100m above mean sea level, including the 3cm hourly to daily correction, are presented in the columns on the right.

Name	Station Elevation (m)	Return periods at 100m above mean sea level			Return periods of snow loadings including +3cm correction		
		50-year (cm)	100-year (cm)	120-year (cm)	50-year (kN/m^2)	100-year (kN/m^2)	120-year (kN/m^2)
Ballyshannon (Cathleen's Fall)	11	23.2	27.9	29.0	0.52	0.62	0.69
Belmullet	8	21.5	25.6	26.7	0.49	0.57	0.64
Birr (merged with Gurteen)	71	16.8	18.7	19.1	0.40	0.43	0.49
Casement	91	38.9	48.2	50.7	0.84	1.02	1.12
Claremorris	67	22.5	25.1	25.8	0.51	0.56	0.62
Clones	70	25.4	28.9	29.7	0.57	0.64	0.70
Cork Airport	162	15.7	19.1	19.9	0.37	0.44	0.50
Dublin Airport	69	25.4	29.0	29.9	0.57	0.64	0.70
Dundalk (Annaskeagh W.W.)	66	19.0	21.7	22.5	0.44	0.49	0.56
Glenealy (Kilmacurragh Park)	129	15.6	21.1	22.5	0.37	0.48	0.56
Kilkenny	61	20.9	23.9	24.6	0.48	0.54	0.60
Malin Head	18	25.5	31.5	33.0	0.57	0.69	0.77
Mount Russell	201	12.4	13.1	13.5	0.31	0.32	0.37
Mullingar	103	17.9	19.3	19.6	0.42	0.45	0.50
Roches Point	25	19.5	21.0	21.4	0.45	0.48	0.53
Shannon Airport	3	17.2	19.4	19.9	0.40	0.45	0.50
Straide	19	24.3	26.8	27.3	0.55	0.60	0.65
Valentia Observatory	8	17.4	20.9	21.9	0.41	0.48	0.54
Warrenstown	81	18.3	28.8	32.4	0.43	0.64	0.75

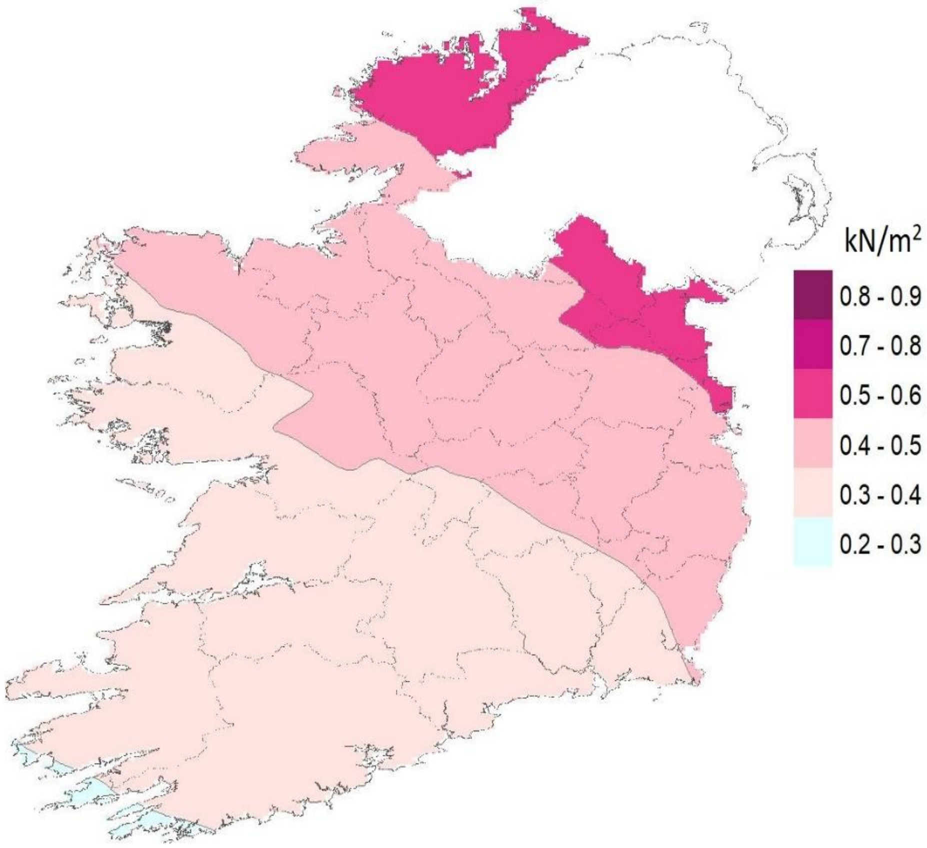

Figure 2: Return values of snow loadings at 100m above mean sea level in Ireland for a 50-year return period.

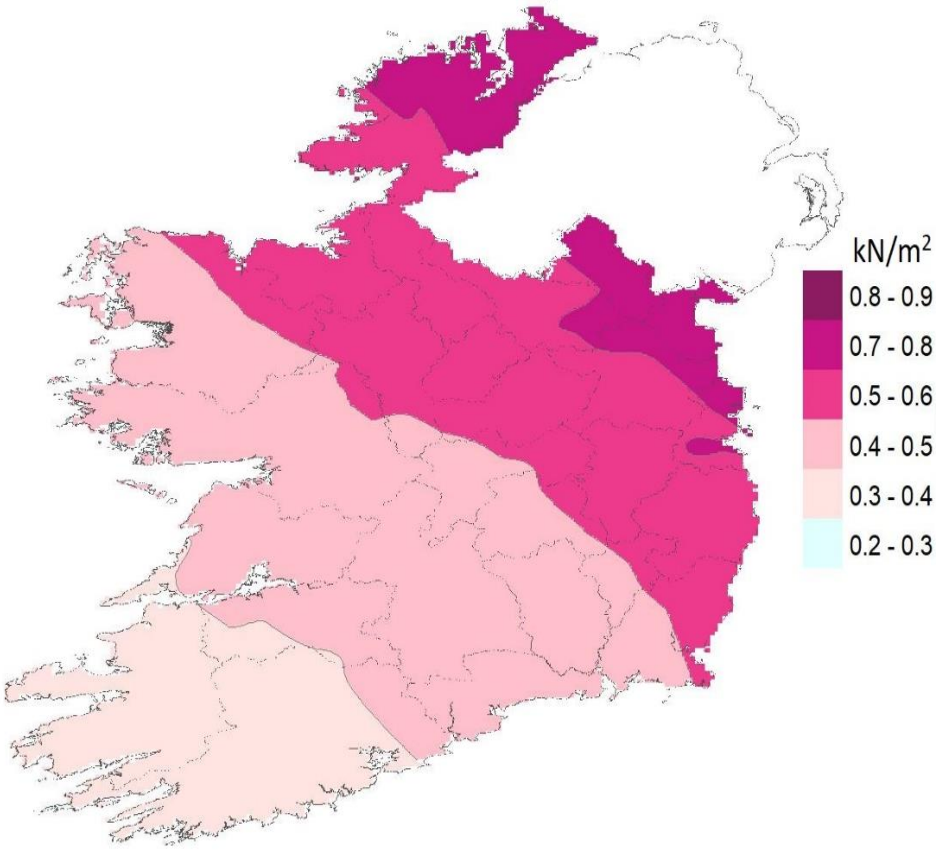

Figure 3: Return values of snow loadings at 100m above mean sea level in Ireland for a 100-year return period.

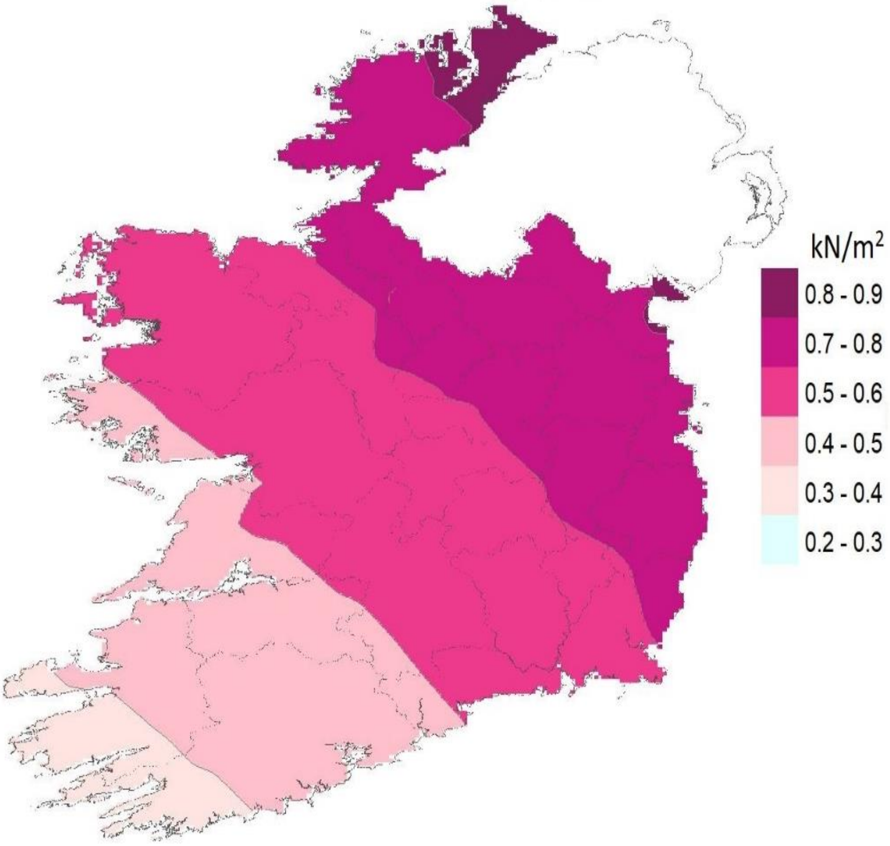

Figure 4: Return values of snow loadings at 100m above mean sea level in Ireland for a 120-years return period.

4. Discussion

The classes of return values of snow loadings in Ireland for the 50, 100 and 120-year return periods have a diagonal geographical distribution and an increase in kN/m^2 from southern to northern areas. The occurrence of snow tends to increase with distance from the west and south coasts, and snow lying is more often recorded in the midlands and eastern areas than in the western part of the country due to an easterly polar continental airflow, where the jet stream has been pushed south. Snow lasts longer on the ground and is more frequent in the north since the temperature decreases with increased latitude. The number of days with snow cover tends to increase northwards through the midlands, corresponding to the decrease in winter air temperatures. Therefore, the maps produced in this research have more representative results and geographical distribution of snow loads than the preceding map of return values of snow loadings in the Republic of Ireland for a 50-year return period at 100m above mean sea level (BSI, 2007; Keeghan, 2010; Government of Ireland, 2012; NSAI, 2015b).

5. Conclusion

Maps of return values of snow loadings at 100m above mean sea level in Ireland for 50, 100, and 120 years return periods have been produced by employing the methodology described in I.S. EN 1991-1-3:2003&AC:2009&A1:2015 (NSAI, 2015a). The new maps will support the structural design of buildings and civil engineering works to enhance resilience in support of climate change adaptation in Ireland.

The new maps of return values of snow loadings at 100m above mean sea level in Ireland for 50, 100, and 120-year return periods should be adopted by stakeholders. These new maps are more representative and supersede the previous map of return values of snow loadings at 100m above mean sea level for 50 years return period (Keeghan, 2010; Government of Ireland, 2012; NSAI, 2015b).

It is hoped that the detailed explanation of the methodology, application of I.S. EN 1991-1-3:2003&AC:2009&A1:2015 (NSAI, 2015a), and the clarification of the rationale for the new maps being more accurate than the preceding map (Keeghan, 2010; Government of Ireland, 2012; NSAI, 2015b) provided here will be of assistance to regulators elsewhere in adopting these new maps in their own jurisdictions.

The new maps produced here represent the worst-case scenario in the current context of climate warming. The sixth assessment report of the Intergovernmental Panel on Climate Change projects decreases in snowfall events, which would be larger at 2.0°C warming or above in comparison to a warming of 1.5°C in the global mean air temperature (IPCC, 2021). Additionally, snowfall in Ireland is projected to decrease substantially by the middle of the 21st century when considering the RCP4.5 and RCP8.5 scenarios (Nolan and Flanagan, 2020).

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Appendix A[1]

Explanatory note – differences between the new map of return values of snow loadings at 100m above mean sea level in the Republic of Ireland for a 50-year return period and the old map (Keegan, 2010; Government of Ireland, 2012; NSAI, 2015b)

An earlier map of return values of snow loadings at 100m above mean sea level for a 50-year return period produced for Ireland had focused the calculations of the greatest snow depth per year based on daily observations from a small network of 10 stations and without stations from Northern Ireland (Keegan, 2010; Government of Ireland, 2012; NSAI, 2015b; Figure A1). Discrepancies were identified in the map produced for Ireland (Keegan, 2010; Government of Ireland, 2012; NSAI, 2015; Figure A1) with the map produced by BSI (2007) for the United Kingdom and Ireland for a 50-year return period. The discrepancies refer to the classification of 0.7kN/m^2 in the Dublin/Wicklow area, another higher snow loading value of 0.6kN/m^2 in the Monaghan region (Clones) and the Southern region is represented as 0.4kN/m^2 (Figure A1). As Keegan (2010) reported, the results should not be considered overly accurate due to the daily resolution of the snow depth observations, the small number of stations and the relatively few years with significant snow.

In this report, Met Éireann employed the methodology described in NSAI (2015a) to produce maps of the return values of snow loads at 100 meters above mean sea level for the return periods of 50, 100 and 120 years for Ireland. The new map of return values of snow loads at 100 meters above mean sea level for a 50-year return period produced in this report (Figure A2) is more accurate than the old map (Keegan, 2010; Government of Ireland, 2012; NSAI, 2015b; Figure A1) and presents more agreement with the preceding map produced for the UK and Ireland (BSI, 2007). The rationale for the new map produced in this report (Figure A2) being more accurate than the preceding map (Figure A1) is described as follows:

1. A total of 33 stations, including 19 stations across Ireland with between 33 and 80 years of data, plus 14 stations from Northern Ireland with between 16 to 64 years of quality-controlled snow depths observations, have been used to calculate the snow load return periods. A total of 13 stations had overlapping daily and hourly snow depth observations, generally from 1990 onwards. The hourly observations for 13 stations were assessed to determine the greatest snow depth per year.
2. The comparison of hourly and once-daily snow depth observations allowed the application of a more accurate correction of +3cm to account for a possible discrepancy between the once-daily recorded snow depth and the actual maximum snow depth over that particular day which can occur at any time over 24 hours. In contrast, Keegan (2010) applied a correction of +2cm.
3. Including stations from Northern Ireland in the data analysis in this research was necessary to avoid discrepancies of outputs in the border region in the map for Ireland.
4. The map gridding methodology employed in R software in this research is more robust than the spline interpolation employed in ArcGIS software to generate the previous map of snow loads (Keegan, 2010; Government of Ireland, 2012; NSAI, 2015b). Specifically, the interpolation of return periods across all grid points is made in two processes: a linear regression of return periods with easting and northing as predictive power and a second step to interpolate the linear regression residuals across grid points using a weighted average of nearest stations to a particular grid point, known as inverse distance weighting.
5. Using a denser network of stations and longer series in this research allowed the generation of more realistic maps of snow loading.
6. The classes of return values of snow loadings have a diagonal geographical distribution and an increase in kN/m^2 from southern to northern areas, resulting in more representative results and distribution of snow loads than the preceding map. The occurrence of snow tends to increase with distance from the west and south coasts, and snow lying is more often recorded in the

[1] Mateus, C., and Coonan, B. 2022. Snow loadings at 100m above mean sea level in Ireland. Climatological Note No. 20. Dublin: Met Éireann.

midlands and eastern areas than in the western part of the country due to an easterly polar continental airflow, where the jet stream has been pushed south. Snow lasts longer on the ground and is more frequent in the north since the temperature decreases with increased latitude. The number of days with snow cover tends to increase northwards through the midlands, corresponding to the decrease in winter air temperatures.

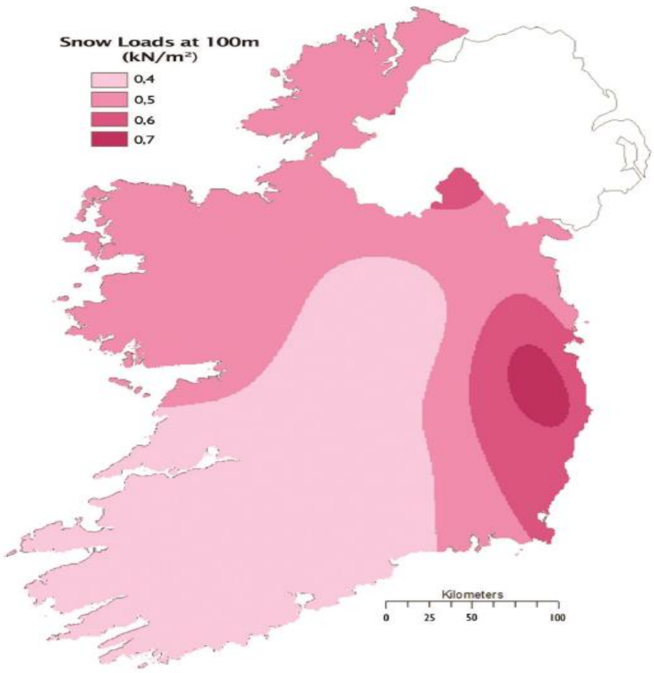

Figure A1: The old map of return values of snow loadings at 100m above mean sea level in Ireland for a 50-year return period produced by Keegan (2010) and published by the Government of Ireland (2012) and NSAI (2015).

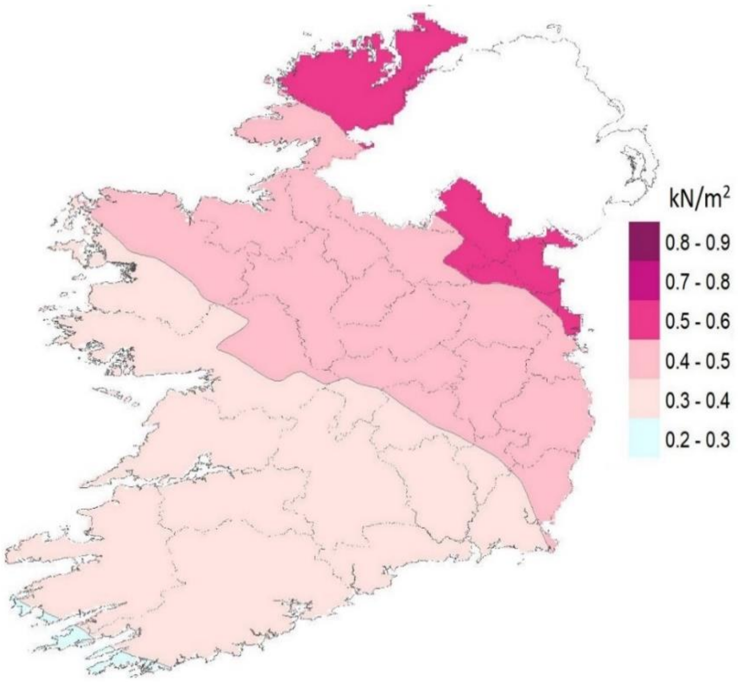

Figure A2: The new map of return values of snow loadings at 100m above mean sea level in Ireland for a 50-year return period, which should be adopted by regulators[2].

[2] Mateus, C., and Coonan, B. 2022. Snow loadings at 100m above mean sea level in Ireland. Climatological Note No. 20. Dublin: Met Éireann.